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Bulletin 84



Precast insulated sandwich panels

fib PCI Precast/Prestressed Concrete Institute

State-of-the-art report

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Bulletin 84

Precast Insulated Sandwich Panels

PCI
Precast/Prestressed Concrete Institute

State-of-the-art report

Task Group 6.11

December 2017

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Approval for this bulletin

Subject to priorities defined by the Technical Council and the Presidium, the results of the *fib*'s work in commissions and task groups are published in a continuously numbered series of technical publications called *bulletins*. The following categories are used:

Category:	**Approval by:**
Technical report	Task group and chairpersons of the commission
State-of-the-art report	Commission
Manual / Guide to good practice / Recommendation	Technical Council
Model code	General Assembly

Any publication not having met the above requirements will be clearly identified as a preliminary draft.

fib Bulletin 84 was approved as a state-of-the-art report by Commission 6 Prefabrication and was drafted by Task Group 6.11, Precast Insulated Sandwich Panels, in Commission 6, Prefabrication.

Many photos, sketches and diagrams have been generously provided from numerous sources, including: BPDL International, Creagh Concrete, CPI Concrete Plant International, Ebawe, Ergon Structural Concrete, FEBE, Halfen-Deha, Hollow Core Concrete, Parma Oy, PCI, Peikko, Ratec, RTT Finland, Techcrete, Thermomass, Universidade Nova de Lisboa, Variotec, Vollert, Weckenmann and Westkon Precast, all of which have been particularly helpful.

Cover images:
Front cover: Flooranaukio Housing, Helsinki, Finland
Back cover: Rampo College, New Jersey, USA

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ISSN 1562-3610
ISBN 978-2-88394-124-3
Proofreading and layout by Marie Reymond from the *fib* Secretariat
Printed by DCC Document Competence Center Siegmar Kästl e.K., Germany

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Acknowledgements

This guide to good practice was drafted by Task Group 6.11, Precast Insulated Sandwich Panels, in Commission 6, Prefabrication.

Authors:

Simon Hughes (Convener/Editor)
Westkon Precast Concrete, Australia

Arto Suikka (Co-Convener/Editor) †
RTT Finland, Finland

George Jones
CDC Ltd, Ireland

Carlos Chastre Rodrigues
Universidade Nova de Lisboa, Portugal

Alessandra Ronchetti
Assobeton, Italy

Venkatesh Seshappa
Thermomass, USA

Antonello Gasperi
Consulting, Italy

Jason Krohn
Precast/Prestressed Concrete Institute, USA

Holger Karutz
CPI Concrete Plant International, Germany

Larbi Sennour
CEG-TX, USA

Gösta Lindström
AB Stränbetong, Sweden

Spyros Tsoukantas
KEF Infrastructure India Pvt Ltd, India

Additional contributors:

Arnold Van Acker
Belgium

Mathias Tillmann
German Association for Precast Concrete Construction, Germany

Sthaladipti Saha
Larsen & Toubro Ltd

Diane Laliberté
BPDL International, Canada

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In memory of Arto Suikka (11.4.1950-15.8.2016)

During the final phase of preparing this Bulletin, we received the sad news of the passing of Arto Suikka. Arto retired from working in 2013 but remained active within the Commission and the Task Groups as a corresponding member until April 2016, when his illness prevented him from further contributing. Arto formed a significant part of the history of the Commission on Prefabrication, both in FIP and in the *fib*, and was loved and respected by all. Arto was characterized by his warm, friendly personality and his complete dedication to all that he was involved in. Arto was always willing to assist and could always be counted on to contribute. The Commission on Prefabrication was very close to his heart, so much so that he often questioned the future of the Commission and its future activities, always looking for the Commission to grow with the industry. Arto always approached things in a positive and constructive way – Arto was unique and a visionary man, he will be sadly missed by all.

Arto was vital to the to the creation of this bulletin and we dedicate this bulletin to him as a tribute.

A good friend to all of us, a friend who has left us far too soon,

Goodbye Arto.

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Foreword

During the mid-20th century, with the rise of industrial prefabrication, precast concrete sandwich panels started being used as cladding for buildings. Since then, society and construction industry have become increasingly aware of energy efficiency in all fields, including affordability and sustainability consciousness, while maintaining the buildings' durability. As such, buildings have been subject to increasingly stringent requirements which has kept the technology of sandwich panels continually at the forefront of building envelope evolution.

Nowadays, sandwich panels have reached the highest standards of functional performance and aesthetic appeal. In building construction, these sandwich panel attributes combine with the well-known advantages of prefabrication including structural efficiency, flexibility in use, speed of construction, quality consciousness, durability, and sustainability. Sandwich panels have gained more exposure, thus representing quite a significant application within the prefabrication industry and a vital component of the precast market.

The *fib* Commission "Prefabrication" is eager to promote the development of all precast structural concrete products and to share the knowledge and experience gained, to aid with practical design and construction. By issuing this comprehensive overview, "Guide to Good Practice", a better understanding of design considerations, structural analysis, building physics, use of materials, manufacturing methods, equipment usage and field performance will be provided. This document contains the latest information currently available worldwide.

The Commission is particularly proud that this document is a result of close cooperation with PCI and that it is published by both the *fib* and PCI. This cooperation started six years ago, first with comparing the different approaches to several issues, then progressively integrating and producing common documents, like this one, that hasn't yet been treated in a specific Guide by either body.

This Guide is intended to be the reference document to all who are interested in utilising the advantages of Precast Sandwich wall panels. In conjunction with the previously published Planning and Design Handbook on Precast Building Structures, the designer will have significant resources to integrate sandwich wall panels into any applicable structure.

The Commission is grateful to all the Task Group members for this accomplishment, particularly to Simon Hughes, who convened and led it successfully.

Stef Maas
Chair of the *fib* Commission 6: *Prefabrication*

Ned Cleland
Chair of PCI *Technical Activities Council*

Simon Hughes
Convenor of the *fib* Task Group 6.11:
Precast concrete sandwich panels

Venka Seshappa
Chair of PCI *Precast Insulated Wall Panels Committee*

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1 Introduction

With sustainability and energy efficiency becoming a major global concern, interest in precast concrete insulated sandwich panels has significantly increased in recent years.

Tighter government controls over greenhouse gas emissions have been a major catalyst within the construction industry to explore more environmentally friendly designs, materials, and construction methods. This exploration has also lead to an increasing awareness of the benefits of passive solar design utilising thermal mass, appropriate solar orientation and air-tightness.

Improvements in the environmental performance of concrete within the construction industry have been applied, with many traditional alternatives now widely accepted, including the use of:

- Recycled materials including aggregates and water,
- Supplementary cementitious materials such as Fly-Ash, Blast Furnace Slag, Silica Fume and Geopolymers, and
- High Strength concrete used to reduce component section sizes and geometry.

However, it is the combined benefits that precast insulated sandwich panels are able to provide that makes this system the material of choice for many buildings.

What is a precast insulated sandwich panel?

Precast insulated sandwich panels are typically comprised of a minimum of three separate layers; an outer layer of reinforced and/or prestressed precast concrete, an insulation layer and an inner layer of reinforced or prestressed precast concrete. The layers are mechanically held together using various types of ties or connectors. Additional layers such as a moisture barrier, air void and/or cladding materials may also be incorporated as shown in Figures 1-1 and 1-2. Please refer to Chapter 4 for further detail regarding each layer.



Fig. 1-1 Example of a Sandwich Panel

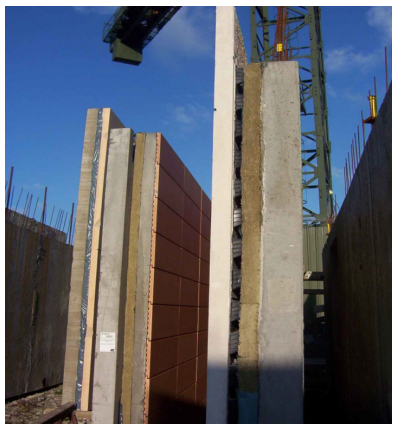


Fig. 1-2 Sandwich Panels

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Precast insulated sandwich panels are able to reduce building energy costs, improve long term performance and make use of more environmentally friendly concrete.

Life cycle analysis and the long-term performance of a building need to be important considerations for all modern structures, with CO_2 emissions from the HVAC (Heating, Ventilation and Air Conditioning) being the greatest contributor to energy usage and resultant CO_2 emissions.



Fig. 1-3 Sandwich Panels Building (Xerox Building, Lisbon Portugal)

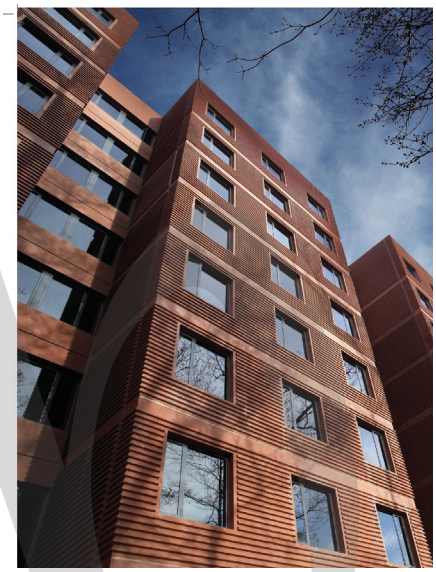


Fig. 1-4 Sandwich Panels Building (Ramapo College, New Jersey)

Achieving a sustainable building solution requires taking a variety of environmental factors into account, from the embodied energy in the construction materials, to the energy consumption during a buildings life - a holistic sustainable solution.

Precast insulated sandwich panels offer significant reduction in energy usage for both heating and cooling, especially when combined with additional passive and active energy saving initiatives (such as passive solar design, use of high thermal mass flooring, appropriate orientation, systems like thermal mass activating flooring systems and mechanical shading). The need for air-conditioning and heating can be significantly reduced or eliminated altogether in some climates. With precast insulated sandwich panels, the reduced U-Value (increased R-Value) and benefits in both the thermal mass and resultant thermal lag provide a building element that is able to provide significant benefits to an environmentally conscious building.

Produced in a controlled factory environment, precast insulated sandwich panels are similar in appearance to solid precast panels, with the distinct difference being their superior thermal and acoustic properties.

Unlike many other systems, precast insulated sandwich panels have the majority of their thermal mass on the inside of the building. This high thermal storage capacity makes them capable of storing and releasing heat very slowly, thereby minimising fluctuations of the internal

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temperature of the building. They also insulate against noise transmission of both airborne and impact sound.

Precast insulated sandwich panels can be used as both the external and internal walls of a building. They can be used as cladding or as a structural element to the building and can have a variety of architectural finishes.

While this document mainly focuses on vertical precast wall panels incorporating two concrete wythes separated by an insulation layer, the same principles may be applied to other precast elements, such as Hollow Core Sandwich Floor and Wall Panels, Double Tee's, prestressed and reinforced floor planks, etc.



Fig. 1-5 Insulated Hollow Core Floor Planks

1.1 Benefits of Precast Insulated Sandwich Panels

Due to the unique manufacturing process, precast insulated sandwich panels offer many benefits to the designer, the builder and most importantly the end user. They are an energy efficient, sustainable, economical, fire resistant, durable, strong and aesthetically versatile building solution.



Fig. 1-6 Le Saint-Jude Apartment Complex in Québec, Canada

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Sustainable

Sustainable often describes a development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The choice of building material can play a significant role in the environmental impact of a construction project and the operation of that building. However, the inherent properties of precast concrete make it a natural choice for achieving sustainability in buildings. Precast concrete contributes to sustainable practices by incorporating integrated design, for example, using material efficiently, reducing construction waste, and minimising site disturbance.

Precast insulated sandwich panels are typically manufactured using local products. Recycled materials such as reclaimed aggregate, recycled steel and water, along with supplementary cementitious replacements, such as blast furnace slag and fly-ash, can be included in the concrete mix. Utilising efficient production methods means a higher quality product with minimal production waste.

Since the sandwich panels are delivered to the construction site on trucks, site disturbance around the construction site is kept to a minimum as no scaffolding is required, as compared to masonry walls. The panels that are delivered are usually picked up from the trucks and installed directly on the building; hence no on-site storage is required. On-site, the use of precast insulated sandwich panels creates less air pollution, noise and debris, and site waste is reduced as exact elements are delivered from local precast manufacturers to the construction site. Sites become safer because they are less cluttered with materials and labour.

Sandwich panels, once in place, create a building envelope that is insulated while serving as an air barrier and a vapour retarder. As will be shown, due to their high thermal mass, internal temperature fluctuations are limited and the resulting energy savings can be quite significant. The high quality of precast insulated sandwich panels means that they can be left exposed internally in order to maximise the benefits of the high thermal mass. Owing to its high density, precast has the ability to absorb and store large quantities of heat. Furthermore, the integrity of precast means that maintenance and operating costs are low. The durability of precast over other materials (including other concrete elements) results in a longer service life.

Economical

Precast insulated sandwich panels can be used for both wall cladding or as a load-bearing structural element. They are similar to solid precast concrete panels for erection purposes and are therefore easily erected by an experienced precast erection crew. When used as structural elements, precast insulated sandwich panels can act as a beam, column, external wall, and insulated internal element all in one, which significantly shortens the construction cycle and reduces the cost of construction.

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Fire Resistant

As precast insulated sandwich panels typically comprise a concrete layer both externally and internally, sandwich panels are inherently fire resistant. Depending on the various types of insulation and connectors adopted, various fire rating levels are achievable. Their inorganic composition also reduces the need for additional fire protection.

Durable

The inherent durability of precast concrete structures is well documented. Using high strength, high quality precast concrete allows for a long service life to be achieved whilst protecting the integrity of the insulation layer. Their long life makes them a cost-effective construction solution. Externally, a variety of available finishes provide architectural freedom whilst requiring minimal maintenance. This equates to on-going cost savings over the life of the building.

Multi-hazard resistant

Since the structural load bearing material is concrete, precast insulated sandwich panels are resistant against blast effects, tornados, chemical attack, bullets, etc. In recent testing, the US Military has shown that precast sandwich panels perform well against blast loads by dissipating blast energy.

Speed of construction

Precast insulated sandwich panels provide the same benefits as other precast systems: they are easy and fast to erect on-site, this results in shortened construction periods and earlier tenancy.

Aesthetically Pleasing

Designers of precast sandwich panels have the flexibility of custom manufacture for size, shape, finish and colour. Precast insulated sandwich panels can be produced with a smooth off-form finish and can be of natural grey colour, or subsequently painted or stained. False joints may be incorporated into the design and mould liners can be used to create an endless array of patterns. Textures can be achieved by acid

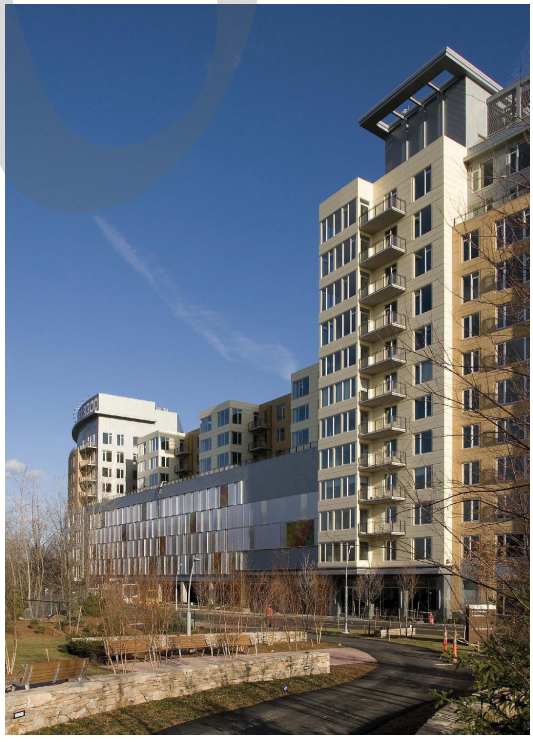


Fig. 1-7 Natick Residence, Massachusetts, USA

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washing, sand (or grit) blasting, honing or polishing, often with an integrated colour pigment, to achieve impressive results. Brick or ceramic tiles or natural stone plates can also be used as an outer surface of sandwich panels.



Fig. 1-8: Completed projects incorporating sandwich panels (Left - Ramos e pereira, Sines, Portugal; Top Middle - Sporting Clube de Portugal, Lisbon, Portugal; Top Right - Manuel Gaspar, Sintra, Portugal; Middle Bottom – Auchan-Jumbo, Castelo Branco, Portugal; Bottom Right - Carrefour, Loures, Portugal)

Energy Efficient

Due to their high thermal mass and insulating properties, precast sandwich panels are able to provide a more comfortable living environment with reduced internal temperature fluctuations. This consistency of internal temperature results in a reduction in energy consuming artificial heating and cooling systems.

The inner concrete layer provides an insulated thermal mass within the building. The heat that is absorbed by this inner layer during the day is released into the building's interior at night when temperatures drop. Precast insulated sandwich panels allow the flexibility for varying thermal performance requirements in different climate zones and/or for different compliance requirements. The component geometry can be adjusted to achieve the desired performance level.

Air Quality

Precast insulated sandwich wall panels have the distinct advantage of providing superior indoor air quality to the occupants. A sandwich panel with concrete on the inside and

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outside surface generally serves the dual function of primary air barrier and vapour retarder eliminating the need for additional materials required with other façade systems. By using edge-to-edge, closed-cell foam insulation in high performance precast concrete sandwich wall panels, the interior concrete is prevented from reaching the temperature at which condensation may occur, thereby reducing the potential for mould. The insulation also acts as a vapour retarder and minimises vapour transfer through the wall. Precast concrete is not a food source for mould as it is not organic. As a result, it does not promote organic growth (mould) even if wetted.

Concrete contains low to negligible levels of volatile organic compounds (VOC) (0.018 mg/m^3) and VOC Emission rate of 0.003 mg/m^{2}h, hence the absence of off-gassing that can cause deteriorated indoor air quality. For most building types, exposed concrete walls do not require finishing material, such as plaster lining or drywall. This prevents particulates from sanding drywall tape seams. However, in some building types, it will be necessary to use form release agents, curing compounds, damp-proofing materials, wall and floor coatings and primers, membranes, sealers, and water repellents. In such buildings, VOCs in concrete construction can be further reduced by using low-VOC materials.

Concrete does not contribute to indoor air quality problems caused by flooding. Concrete is not damaged by water. Concrete submerged in water absorbs very small amounts of water over a long period of time.

1.2 Understanding Thermal Mass

Historically, the benefits of thermal mass have been well understood for centuries. However, in today's environment, there has been a growing trend towards lighter structures. It is well accepted that high thermal mass and the resultant thermal lag can have a significant positive influence on the internal environment of a building. Having a building of high thermal mass will produce a structure that is able to even out large temperature fluctuations and significantly reduce peak temperatures that are common in light weight construction.

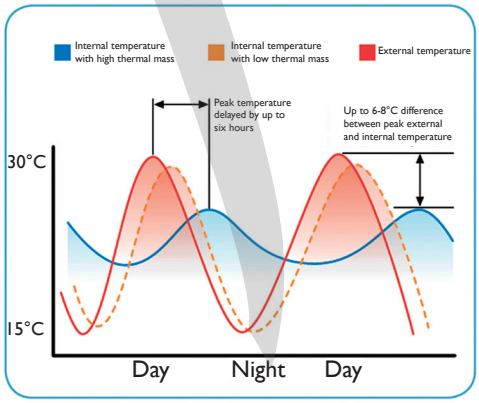


Fig. 1-9 Thermal Mass Diagram (From the Concrete Centre: Thermal Mass Explained)

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The thermal mass (thermal capacitance or heat capacity) is measured as the amount in which a material is able to store energy and release it back to the environment as required. Concrete has the highest volumetric heat capacity of any common building material and as a result can provide significant benefits in smoothing out a buildings indoor temperature. The resultant indoor environment is commonly accepted as a more comfortable space without the need for heated or cooled air to be forced into a space.

The effects of thermal mass can vary with the climate and the building use. However, a concrete sandwich panel will almost always provide both reductions and delays of the peak temperatures affecting a building. Therefore, even with equal U-values, a concrete sandwich panel will provide greater energy savings than a solid wall constructed of lightweight (low mass) materials. This effect is recognised by the major building codes and can be considered during the building design.

The result of this high thermal mass is a significantly reduced need for high energy using air conditioning, and/or space heating systems. It is commonly accepted that between 40-50% of a household's energy usage is due to the heating and cooling of the indoor environment; thus, a significant reduction of the need for this heating or cooling will result in significant energy saving and resultant CO_2 reductions.

When considering the life cycle assessment of a structure, it is important that it be considered from 'cradle to grave' or 'cradle to cradle' (life cycles) so that the full environmental impact of a building is recognised.

It is important to consider the structure as a whole; and while thermal mass and thermal lag will provide significant advantages, a holistic approach to energy efficient design must be considered. Consideration must be given to building orientation to maximise the solar benefits, including shading, window sizing, etc. Windows need to be carefully considered with double or triple glazed options, as well as the air tightness of the structure.

Insulation is widely accepted as a benefit to assist with internal comfort. The combination of insulation and the benefits of materials with high thermal mass result in a superior building material. To gain the most from the system, it is vital that the insulation is located behind the majority of the thermal mass and, wherever possible, allow the thermal mass to be exposed to the internal space.

Precast insulated sandwich panels are able to provide the best of both worlds. They provide the benefits of a structure with high thermal storage capacity and incorporate insulation that is able to keep the thermal energy where it is required; indoors. The result is a structure that is able to provide a very consistent indoor environment that requires very little mechanical intervention to keep it comfortable.

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1.3 Understanding Acoustics

A comfortable living environment does not only depend on the ability of a building to provide a comfortable internal temperature; it must also consider the buildings acoustics. A quiet living environment or a building with a high Weighted Sound Reduction Index (Rw) rating is considered to be more desirable and more comfortable.

Precast insulated sandwich panels provide outstanding acoustic performance. This is achieved by the density and high mass of concrete, making it good for controlling reverberation. This, along with the inclusion of the insulation layer acting as an internal 'buffer', result in precast insulated sandwich panels being efficient at blocking out noise.

The minimum three layers of absorbent material also provide vibration control as they are able to dampen vibrations caused by things such as machinery. The need for additional systems to control vibrations is reduced and interior comfort enhanced.

Unwanted noise, such as airborne noise and impact noise, can effectively be blocked by precast insulated sandwich panels, providing that joints and openings are detailed and sealed correctly. Poorly sealed joints and openings can lead to unwanted noise entering a space, reducing the buildings sound attenuation properties also known as flanking. One of the benefits of precast concrete buildings is that they normally have fewer joints or voids than other forms of construction, improving their acoustic qualities.

As a result, precast sandwich panels are ideal for buildings, particularly in already built residential areas, or for buildings with significant external noise, such as near major arterial roads to block out traffic noise, in industrial settings, etc. In apartment buildings, residents can also benefit from the acoustic sound attenuation properties of precast insulated sandwich panels acting as the common wall or internal partition.

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1.4 Global use of Precast Insulated Sandwich Panels



Fig. 1-10 Buildings with Precast Insulated Sandwich Panels in Russia [Ebawe], Dubai [Ebawe], France [Vollert] & Québec [BPDL]

Precast insulated sandwich panels are used for many purposes in many countries around the world. Besides being used for residential, office, commercial and industrial buildings, precast insulated sandwich panels can also be used for schools, hospitals, cold stores, controlled atmospheres, prison walls, etc.

A recent survey showed that, in some countries, precast insulated sandwich panels have been used for more than 50 years. Nowadays, mainly due to increasing awareness of energy efficiency aspects and energy saving housing design concepts, interest for the use of precast insulated sandwich panels has increased.

Throughout the world, a tendency to reduce U-values (increase R-values) for outer walls is widely accepted as a future trend in the construction industry; with precast insulated sandwich panels, this can be achieved. Different climates in different countries lead to different requirements worldwide. As can be seen following, in general, the requirements are not as onerous in warmer climates.

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- In Spain, U-values of 0.74 W/m²K are considered to be sufficient (and vary throughout the country)
- The United States demands U-values of 0.34 W/m²K for certain buildings (Note: USA uses R Values, where R = 1/U in $ft^2 \cdot °F \cdot hr/Btu$)
- France require U-values of 0.22 W/m²K from 2012
- Ireland and UK are becoming more restrictive, with a target requirement in the order of U = 0.18 W/m²K and 0.20 W/m²K, respectively
- In cold climates, such as in Finland, the maximum U-value can be 0.17, but U-values of 0.10 W/m2K for the outer walls of passive energy houses is required. With the development of sandwich panels, these types of figures are achievable.
- Australia prescribes different R-values for outer walls (Note: Australia uses R=1/U values). Converted to U-values, the future range of required U-values will be between 0.26 W/m²K and 0.56 W/m²K. Australia will also allow an adjustment in U-value depending on surface density and shade angle.
- In Germany, future requirements for outer walls will most likely not exceed U=0.28 Wm²K. However, the overall building energy efficiency needs to be guaranteed.



Fig. 1-11 City of Miami College of Policing, Miami, USA

From this we can see that different countries with diverse climates and varying requirements are following many concepts for the common goal: the reduction of the carbon footprint, energy savings and getting closer to a totally sustainable environment.

In many countries, Expanded or Extruded Polystyrene (EPS/XPS) or Polyurethane (PUR/PIR) as insulation material with thicknesses of 50-75 mm are commonly used; France and Germany are producing precast insulated sandwich panels with up to 200 mm of insulation material, while in Scandinavian countries, mineral wool is often used as the insulation material with thicknesses of up to 240 mm. Development of the precast insulated sandwich panels system will continue with producers developing products such as vacuum insulated panels, providing excellent U-values with significantly reduced thickness, as well as new connection systems continuing to develop.

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Fig. 1-12 High rise buildings with Precast Insulated Sandwich Panels are realised as well. Examples from Finland (16 and 26 stories high), and Sporting Clube de Portugal, Lisbon Portugal



Fig. 1-13 Precast insulated sandwich panels with mineral wool insulation [Weckenmann]

In most countries, non-ventilated precast insulated sandwich panels, or sandwich panels without air gaps, are the most common solution.

To connect both wythes of precast insulated sandwich panels, different types of connectors can be used. Connectors are typically made of steel, stainless steel, fibreglass, carbon fibre or fibre-reinforced polymer (FRP) composites. In addition to the connector capability to transfer shear flow and connect the two wythes, their thermal conductivity, or thermal bridging, must be considered.

Precast insulated sandwich panels can be designed as non-composite, partially composite or fully composite (refer to Chapter 2 for definitions). Details for the structural design concepts of sandwich panels will be covered in more detail in Chapter 4 of this publication.

With the continued use and development of sandwich panels, more building designers will realise the potential of this type of building element.

The typical panel size varies from country to country. In Finland and France, precast insulated sandwich panels have typical dimensions of 4-6 m x 3-4 m. In Spain, Germany,

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Australia, UK and Ireland, the average measurements are about 8-12 m x 2.5-4.0 m. All of the above are typically produced in precast plants, either on stationary production facilities or on circulating pallet plants. In the United States, precast insulated sandwich panels are also produced on-site with tilt-up technology.

These panels can also be produced up to 20 m length and more, in many cases with one or both wythes being prestressed, on long line beds such as with hollow core slab production. While typical precast insulated sandwich panel measurements of approximately 15-40 m² are used for residential, public or office buildings, large panels with 40+m² are mostly used for industrial and commercial buildings.



Fig. 1-14 Prec. insul. sand. panel with integrated installation for heating and electricity in Austria [Ratec]

Precast insulated sandwich panels are very functional in reducing energy demand and creating a more comfortable environment, but they are increasingly being used for architectural purposes. Coloured concrete, polished or differently treated concrete surfaces – even graphics and pictures may be applied on the outer wythe of the panel.

In Finland, sandwich panels are often "pre-"plastered inside the production plant, and on-site additional layers of coloured plaster guarantee a perfect surface finish, without any visible joints.



Fig. 1-15 Sandwich panel with EPS insulation, produced in Sweden [SommerAnlagenbau]



Fig. 1-16 Pre-Plastered Precast Insulated Sandwich Panel as used in Finish Apartment Buildings

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Plastering is completed on-site to avoid any visible joints



Fig. 1-17 Plastering for apartment building in Finland in Helsinki city [Parma Oy]

The majority of structures using insulated sandwich wall panels are low-rise buildings, up to 5 levels. However, sandwich wall panels have been used in mid-rise (5-10 levels) and high-rise structures (10+ levels), showing that precast insulated sandwich panels are suitable for many applications.



Fig. 1-18 Some architects wish to hide the joints between the panels. This example from Finland shows an ability to hide joints very effectively.

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Fig. 1-19 Photo of 'The Century', Los Angeles, USA.

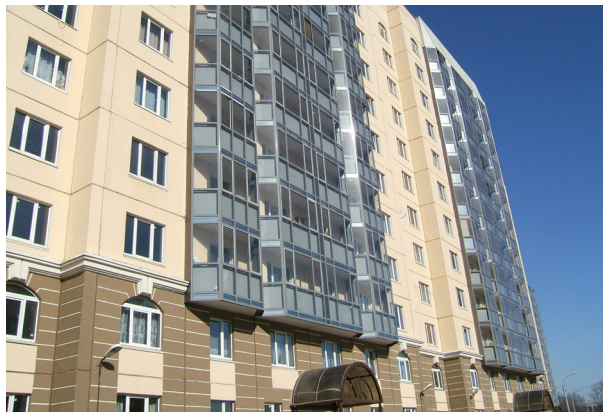


Fig. 1-20 Sandwich panels with a variety of architecturally treated surfaces in Russia [Weckenmann]





Fig. 1-21 Maria Mughal (artist) has designed this graphic concrete figure (Helen of Troy). Left panel as produced, right as installed (University Apartment Building, Joensuu, Finland)



Fig. 1-22 Part of the completed complex (University Apartment Building, Joensuu, Finland)



Fig. 1-23 Industrial Building (Parma, Italy)

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2 Definitions and Notations

Throughout the world, varying terminology is used to describe these types of elements. The following shall be adopted within this document:

Each of the parts that make up the element shall be referred to as 'layers' or 'wythes', while the complete assembly shall be referred to as a panel. A number of panels along a continuous elevation shall be referred to as a 'wall'. For example, a typical sandwich panel is made up of three individual layers, including the inner and outer layers being of precast concrete with an internal insulation layer. When installed, they create a complete wall.

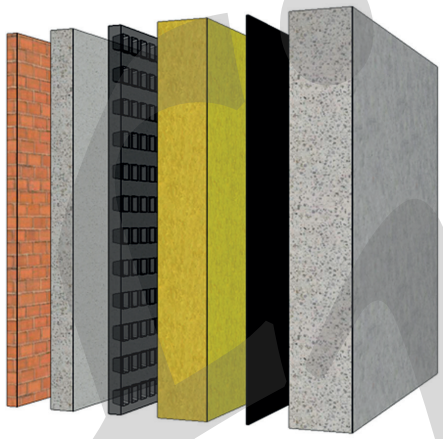


Fig. 2-1 Illustration of the Layers to make a Sandwich Panel

Descriptive terminology is used throughout this document. Some of the common terms relevant to structural design and detailing of precast insulated sandwich panels are explained as follows:

Loadbearing Precast Insulated Sandwich Panel: A precast insulated sandwich panel that supports vertical loads applied by other construction elements.

The loadbearing precast insulated sandwich panels are also subjected to other actions such as their own self weight, loads applied to their surface area, seismic actions, thermal actions and actions due to the shrinkage of the concrete.

The loadbearing precast insulated sandwich panels are commonly used to support vertical loads applied by floor or roof.

Non-loadbearing Precast Insulated Sandwich Panel: A precast insulated sandwich panel that does not support any vertical loads applied by other construction elements.

The non-loadbearing precast insulated sandwich panels are subjected to their own weight, to loads applied to their surface area and to other action as seismic actions, thermal actions and actions due to the shrinkage of the concrete. Non-loadbearing Precast Insulated Sandwich Panel are commonly used for cladding.

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Composite Precast Insulated Sandwich Panel: a precast insulated sandwich panel in which the inner and the outer concrete wythes – during the design life of the structure – act together as a fully composite unit, to resist applied loads and actions.

A composite precast insulated sandwich panel acts as a single unit in bending; complete shear transfer is provided between the inner and the outer wythe by means of rigid ties or connectors, or other tested devices that connect the two wythes.

Non-Composite Precast Insulated Sandwich Panel: a precast insulated sandwich panel in which the inner and the outer concrete wythes, during the design life of the structure, act independently to resist applied loads and actions.

Generally, the inner concrete wythe is the supporting wythe (which is also the structural wythe) and the outer concrete wythe is the supported one. However, the outer wythe may be the supporting wythe as, for example, in the case of vertically spanning double tees with external ribs, used in industrial applications. The supporting wythe may be ribbed.

All loads and actions applied to the supported wythe are ultimately transferred by means of specific devices to the supporting wythe.

Partially Composite Precast Insulated Sandwich Panel: a precast insulated sandwich panel in which the inner and outer concrete wythes, during the design life of the structure, do not act as a fully composite unit, but somewhere in between the Composite Panel and Non-Composite panel, to resist applied loads and actions. Partially composite precast insulated panels have shear ties connecting the wythes, but the connectors do not provide full composite action. The bending stiffness and strength of these panel types fall between the stiffnesses and strengths of fully Composite and Non-Composite precast insulated panels.

The "degree of composite action" depends on the type, stiffness and number of shear ties provided between the inner and outer wythes. This "degree of composite actions" should be determined by calculation and should be specified within the design documents.

Thermal Conductivity (λ): is the time rate of a heat flow by conduction through a unit thickness of a homogeneous material under steady-state conditions per unit area, per unit temperature gradient in the direction perpendicular to the isothermal surface. It is expressed in watts per metre of thickness of material per degree Kelvin (W/mK).

Certified test results of thermal conductivities (i.e. λ -values in W/mK) for the products should be obtained from individual manufactures.

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Table 2-1 Materials thermal conductivity

Material	**Thermal conductivity [W/mK]**
Air	0.024 - 0.025
Aluminium	204 - 250
Brick	0.15 - 1.31
Concrete	1.44
Cork	0.04 - 0.07
Cotton or Plastic Insulation-foamed	0.03
Epoxy, thermally conductive	0.682 - 1.384
Expanded polystyrene - EPS	0.03 - 0.04
Extruded polystyrene - XPS	0.03 - 0.037
Fiberglass or Foam-glass	0.045
Glass	0.8 - 1.4
Limestone	1.26 - 1.33
Marble	2.07 - 2.94
Mineral Insulation or Wool (Felt/Glass/Rock)	0.033 - 0.041
Perlite, (1 atm)	0.031
Polyethylene High Density	0.42 - 0.51
Polyurethane foam	0.02 - 0.021
Steel, carbon	36 - 54
Steel, stainless	16 - 24
Vacuum	0
Water	0.563 - 0.609
Wood, oven-dry	0.04 - 0.17

U-Value: is the heat transmission, in unit time, through unit area of an element (material or construction) and the boundary air films, induced by unit temperature difference between the environments on each side.

This is stated in watts per square metre per Kelvin (W/m^2K). It should be noted that thermal bridges need to be considered in U-value calculations.

R-Value: is expressed as the thickness of the material divided by the thermal conductivity. In most countries, R-Values are given in SI units, typically as square metre kelvin per watt or m^2K/W, while in the United States, R-values are given in units of $ft^2°Fh/Btu$. It is important not to confuse the two R-Values as they are often cited without their units, and the United State R-Values are approximately six times SI R-Values. For R-Values, the higher the number, the more effective the material as an insulator. The R-Value is the reciprocal of the U-Value (R=1/U)

Thermal Mass: is the term used to describe the ability of a material to store heat (or thermal storage capacity). The basic characteristic of materials with high thermal mass is their ability

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to absorb heat, store it and release it at a later time. Thermal mass is the amount of heat (in joules) required to raise the material's temperature by 1 °K or 1 °C.

Thermal Bowing: a strain gradient between the inside and outside of a wall panel can cause the panel to bow. In a precast sandwich panel, the strain gradient is mainly due to temperature difference between the inside and outside. The temperature difference in summer months can be as much as 40°C (72°F) for an ambient temperature facility and would be more for cold storage facilities.

Moisture differences between the inside and outside of an enclosed building can also cause bowing; however, the calculation is much less precise and involves more variables. The exterior layer of the sandwich panel absorbs moisture from the atmosphere and periodic precipitation, while the interior layer is relatively dry, especially if the building is heated. This causes the inside layer to shrink more than the outside, causing an outward bow. The outward shrinkage bowing would tend to balance the theoretical inward thermal bowing in cold weather, which is believed to explain the observation that "wall panels always bow out".

Usually, the magnitude of bowing is not very significant, but in case of sandwich wall panels, it may cause unacceptable separation at the corners of the building and possible damage to the joint sealants. It may therefore be desirable to restrain bowing with one or more connections between the panels. However, this (these) restraint(s) could cause secondary moments and forces that should be accounted for in the design of the panels.

The magnitude of bowing depends on the shear transfer provided by the connectors between the interior and exterior layers. Typically, the composite panels bow more than the non-composite panels.

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3 Energy efficiency, materials, humidity and acoustic performance

3.1 Introduction

Over the past few years, environmental impact and sustainability have become global issues. This has been linked with accelerated population increase and the ever-growing demand on the world's limited resources, due to improved standards of living resulting from greater individual wealth. One of the many consequences of this trend is for people to live in closer proximity to one another, but also to expect a higher degree of comfort, privacy, safety and security than experienced by previous generations.

Buildings and their construction are part of this process. Buildings need to be more energy efficient in use, and to have less embodied energy in their constituent parts.

Precast insulated sandwich panels can contribute towards sustainability as well as other benefits that are expected in homes. It will be shown that significant energy savings are achieved. Careful design, specification and attention to detail will reduce embodied carbon. Concrete itself has the inherent properties to achieve high levels of fire resistance, durability, soundproofing and strength, and the building formed by precast insulated sandwich panels will be resistant to climatic extremes.

Precast insulated sandwich panels are typically formed by 3 layers, the outer and inner layers made of concrete and a thermal insulation layer between them. In some countries, the outer layer can also be made of plaster. The inner and outer layers are typically joined by mechanical connectors. These mechanical connectors are used as structurally required.

A variety of connectors are available. When high conductivity connectors (i.e. metal) are chosen, they are used sparingly because of the thermal (cold) bridges they may create.



Fig. 3-1 IR camera pictures show the energy efficiency and air-tightness of precast insulated sandwich panels [ENOTHERM – Institute of Energy-Optimised Construction, Bochum; Hering Bau GmbH & Co. KG, Burbach]

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The inner concrete layer is typically 80-200 mm and the outer layer 60-80 mm thick. Typical thermal insulation materials include: mineral wool, expanded and extruded polystyrene, polyurethane, and many more, with typical thicknesses of 50-300 mm depending on the local climate requirements. In some precast insulated sandwich panels, the thermal insulation and the structure as a whole can be ventilated to reduce potential moisture in the structure.

All details or connections creating thermal bridges should be avoided. Some examples of how this may be achieved are shown below:

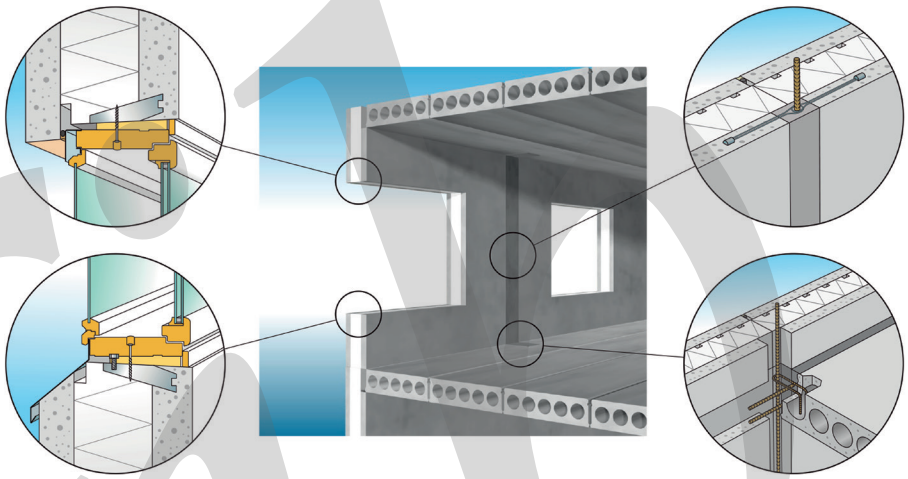


Fig. 3-2 All the connections must be properly detailed to provide a continuous insulation layer and to avoid thermal bridging.

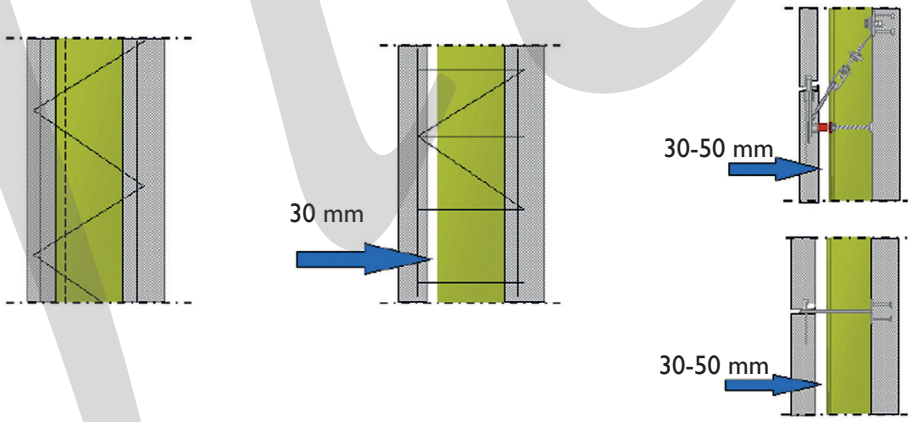


Fig. 3-3 Sandwich panels may be ventilated. In some countries, the insulation sheets with vertical ventilation channels are provided to the outer surface.

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3.2 Energy efficiency demands

3.2.1 Cold Climate

Precast insulated sandwich panels are commonly used in both cold and warm climates.

In cold climates, such as Northern Europe, Northern United States and Canada, where temperatures stay below freezing for long periods of time during winter, the external temperature along with the extent of heating are important considerations in the panel design.

The panels must have adequate thermal insulation with the building being adequately sealed. Air leakage can compromise the ventilation system, which in turn increases heating energy consumption considerably.

Cooling is also required in cold climates, particularly in offices and residential buildings. As shown previously, due to environmental requirements and energy saving initiatives, building codes worldwide have changed, or are expected to change in the near future. With these changes, thicker and more efficient insulation materials will be required.

More and more low, passive and zero energy buildings are being constructed. Precast insulated sandwich panels are ideal for these buildings because of their high thermal mass, air tightness, durability and flexibility in thermal performance.

3.2.2 Hot Climate

It is in hot climate conditions that the thermal performance versatility of high mass walls becomes evident. In these environments, daily outside air temperatures may not fall below 40°C and can rise above 50°C regularly. Hot outdoor air temperatures and direct sunlight heat the outer layers through the day, while night time temperatures may only fall to 30°C. In this situation, a wall's thermal mass and insulation layer provide a valuable thermal delay – or thermal lag – for the interior spaces.

When exterior temperatures increase during the day, the interior mass of a sandwich wall heats up slowly. It may take as long as 6 hours or more of constant exterior heating for the interior face of the mass wall to reach excessive temperatures. That time differential translates into a shorter time spent cooling the building or a cooling load lag time called the Thermal Time Constant or TTC. A larger TTC indicates a longer delay for heat transmission through a wall assembly. It is important to cool the interior mass at night quickly to dissipate any radiant heat from the interior mass of the panel, and to allow the largest lag time possible the following day.

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Even in hot climates a cooler winter season is normal. Sandwich walls will benefit a building's efficiency during these seasonal periods by storing heat during the day and slowly releasing it at night to help provide a constant, comfortable interior temperature with minimal mechanical aid.

For these reasons, sandwich walls in hot climates can provide a versatile and flexible solution to summer cooling inefficiencies and still provide efficient winter insulation.

Special consideration should be given to the design and construction of precast insulated sandwich panels in hot climates. High temperatures and extreme climate conditions can require the usual sandwich wall construction and design techniques to be refined in an effort to create panels and buildings suited to perform at the highest level. The areas highlighted in Figure 3-4 are regions where heating degree days totals are minimal or non-existent for ambient interior temperature buildings. Energy consumption used by a building's heating and cooling systems mainly derives from cooling requirements in these areas.

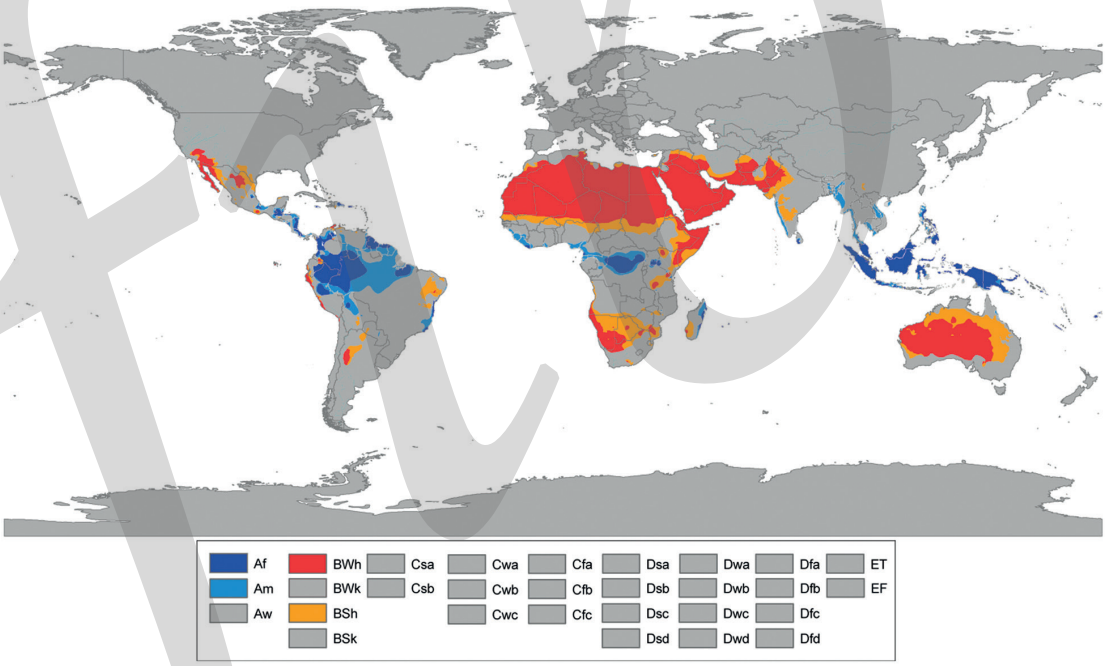


Fig. 3-4 Hot climate zones according to the Köppen classification system.
Af = Tropical Rainforest-No dry Season,
Am = Tropical Monsoonal-Short Dry Season
BWh = Subtropical Arid Desert-Low Latitude Desert,
BSh = Subtropical Arid Steppe.Hot
(Images from the "Updated world map of the Köppen-Geiger climate classification"

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A well-sealed envelope is very important in these climates as any hot air infiltration into a building's interior can drive cooling costs upward. Air infiltration can cause condensation on sandwich panel faces due to interior and exterior differences in humidity and temperature. A wall with properly sealed joints and well-designed panel configurations will perform without any air infiltration or condensation issues. See Chapter 4 for detailed information and suggestions in sandwich wall designing.

The durability of concrete as a building material coupled with the insulative and thermal mass performance of sandwich wall panels make them an ideal choice for projects in hot climates.

3.3 Insulation materials

Various thermal insulation materials have different resistance against heat, fire, sound, compression and moisture. The thermal capacity is typically referred to as λ design or designated as a K value.



Fig. 3-5 Sandwich panels with polyurethane insulation.

Some commonly used insulation materials include mineral wool, such as rockwool and glasswool, expanded or extruded polystyrene (EPS, XPS) and polyurethane (PUR, PIR).

However, the types of insulation are constantly changing and developing with various vacuum systems and gel materials currently under development.



Fig. 3-6 Sandwich panels with mineral-wool insulation



Fig. 3-7 Sandwich panels with EPS-graphite insulation



Fig. 3-8 Sandwich panels with EPS insulation

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Table 3-1 Measured properties of different insulating materials. Compression strength is measured with 10% deformation.

Insulation type	Thermal conductivity	Compression strength	Moisture penetration	Fire safety classification	Typical density	Maximum Temperature
	λ design W/mK	kPa	x10^{12} kg/msPa		kg/m^3	°C
Rockwool	0.034 - 0.041	5 – 30	150	A1	80	1000
Glasswool	0.033 - 0.039	10 – 30	150	A1 or A2-s1d0	50	200 - 600
EPS	0.030 - 0.040	60 – 100	3 - 7	D or E	20	80 - 110
XPS	0.030 - 0.037	150 – 250	1,5	E	20	70 - 100
PUR	0.023 - 0.027	100 – 250	0,1 - 1,2	D or E	40	100 - 250
VIP	0.004 - 0.008	0	0	D or E		100

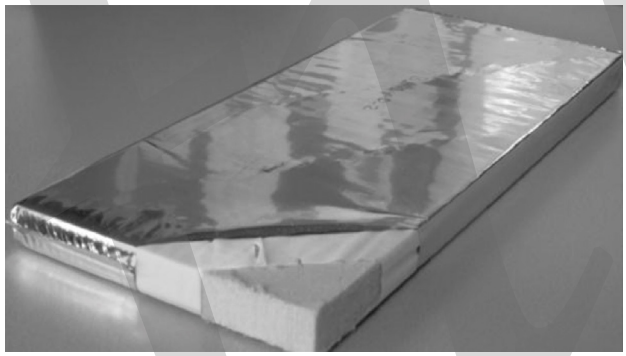


Fig. 3-9 New vacuum insulation type with aluminium laminate surface

A relatively new opportunity for sandwich panels is the possibility to make use of vacuum insulation panels (VIP) for the insulation layer. With integrated vacuum insulation, concrete wall elements having an insulation thickness of 150 mm can reach U values of 0.06 W/m^{2}K. Alternatively, to reach the same U value with EPS insulation (λ = 0.03), a 500 mm insulation layer would be needed.

However, vacuum insulation panels are quite fragile, and are to be handled very carefully to ensure that the internal vacuum is not compromised. As such, special attention has to be given to the anchors connecting the inner and outer concrete layers. Notwithstanding, solutions to integrate VIPs into precast sandwich panels already exist. The figures below (Fig. 3-10 and Fig. 3-11) show some examples of how VIP's can be integrated into precast insulated sandwich panels.

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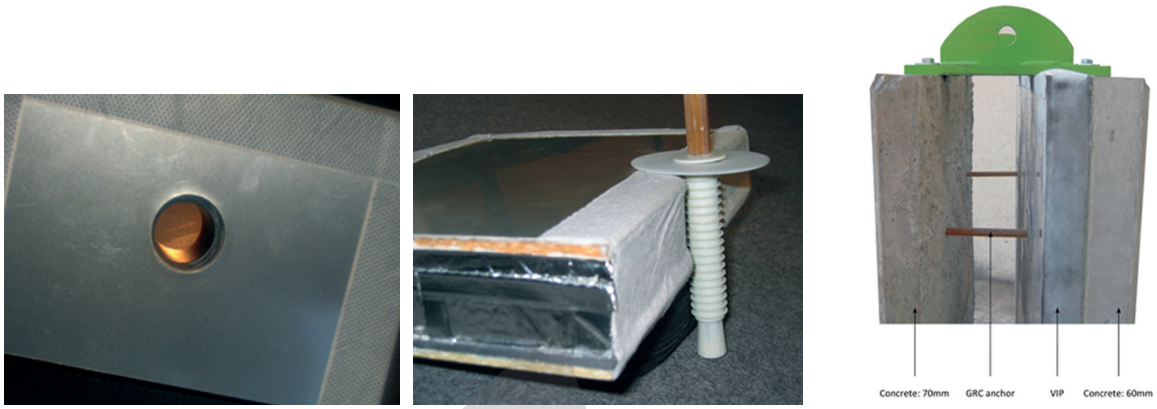


Fig. 3-10 Integration of vacuum insulation panels into sandwich wall elements [Variotec]



Fig. 3-11 Building with vacuum insulated sandwich wall panels [Variotec]

3.4 Panel connectors

The primary purpose of the connectors is to tie the outer layer to the inner layer. These connectors can also create partial or total composite action between the outer and inner layers as previously noted. Within the sandwich structure, forces from wind and other horizontal loads, along with vertical loads need to be considered. Restraints from temperature and other long term deformations also need to be taken into account, with the forces within the connectors dependent on the stiffness.

Connectors are typically manufactured out of steel, stainless steel, fibreglass, carbon fibre or fibre-reinforced polymer (FRP) composites. They are commonly located at between 600-900 mm spacing (spacing of up to 1200 mm is not uncommon for steel ties), with additional connectors provided around openings within the panel.

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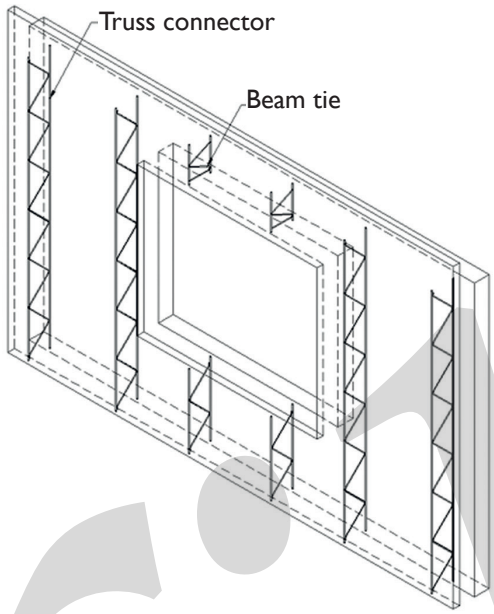


Fig. 3-12 A stainless streel truss connector [Peikko]

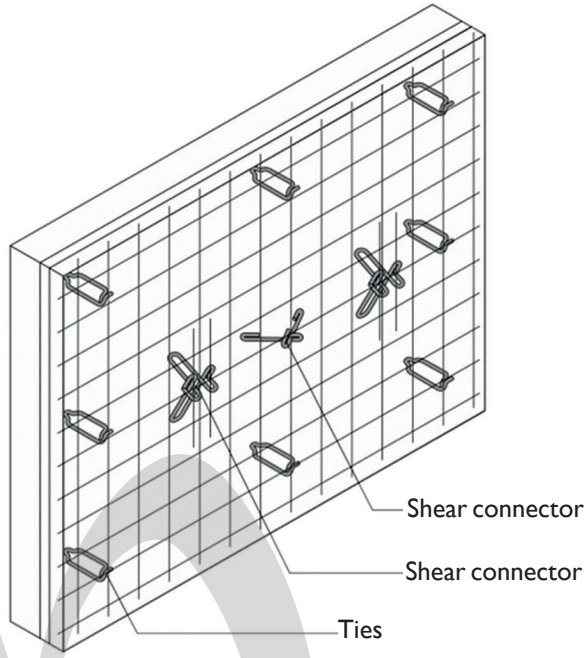


Fig. 3-13 A stainless steel tie [Halfen-Deha]

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4 Structural design and detailing

4.1 Introduction

Precast insulated sandwich panels have been used throughout the world for over fifty years and design methods and details have been developed over that time to keep pace with the expanding appeal for this product.

Most precast concrete products used for wall construction can also be incorporated as part of a sandwich panel. Consequently, the design of a sandwich panel is similar to that of typical precast concrete elements, both prestressed and reinforced, although careful attention to the relative interaction of the components of the sandwich panel is required.

In order to start the design of a precast insulated sandwich panel, one must firstly consider the makeup of the overall panel. A diagram of the possible component parts is illustrated below:

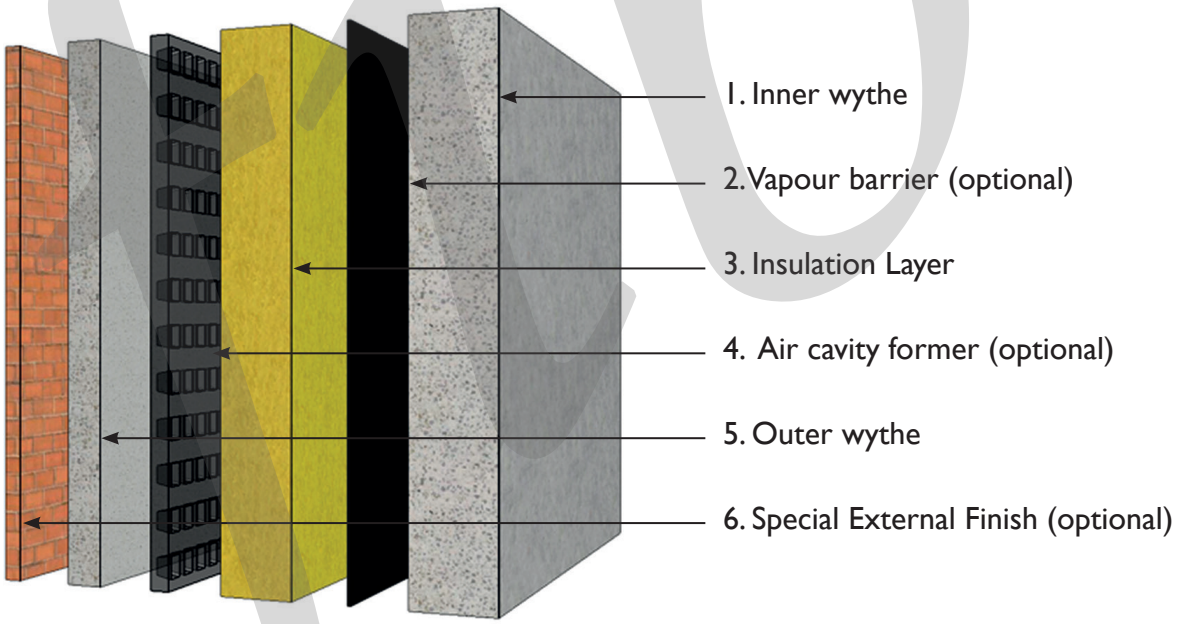


Fig. 4-1 Possible compound parts of a precast insulated sandwich panel.

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A precast insulated sandwich panel may consist of up to six layers, as shown in Figure 4-1, but often has only three layers:

Layer 1 The rear face or inner wythe, generally the concrete loadbearing element.

Layer 2 A vapour barrier separating the inner wythe from the insulation (Optional – location to be specified).

Layer 3 The insulation layer.

Layer 4 An air cavity (Optional).

Layer 5 The front face or outer wythe, generally the concrete non-loadbearing element. Can also be a cementitious render material in place of a concrete layer.

Layer 6 The front face cladding of the outer wythe. Can be materials such as stone, brick or terracotta. Various external rendering systems are also possible in residential applications (Optional).

A sandwich panel would always include Layers 1, 3 and 5. Use of Layers 2, 4 and 6 are dependent on the application and specification. The internal and external concrete wythes (Layers 1 and 5) are joined by structural connectors that normally are proprietary systems manufactured from materials such as steel, stainless steel, fibreglass, carbon fibre or fibre-reinforced polymer (FRP) composites.

Sandwich panels have been popular in Northern Europe and North America for many years, but they have gained in popularity due to increased demand for energy conservation and prefabrication. National requirements for reduction in energy loss through the building fabric (U-values) has generally involved increasing overall panel thickness. U-values in excess of 1.0 W/m²K forty years ago had been reduced to 0.4 by the mid-nineties and requirements are now between 0.30 and 0.15 for many countries. These changes have typically resulted in greater insulation thickness with resulting increases in design forces acting on the concrete wythes. While thermal bridging of the insulation layer may have been long ignored, it now must be considered as part of the structural design process, particularly in the choice of material for the wythe structural connectors.

There have been comparisons between different types of insulation and U-value requirements in Chapter 3. If we take the example of an internal wythe of 150 mm thickness paired with an external wythe of 65 mm and consider expanded polystyrene (EPS) as the insulation layer to achieve a U-value of 0.27 we find that a thickness of 100 mm is required. However, to achieve a U-value of 0.10, an

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insulation layer thickness of 335 mm would be required. Therefore, due to the additional insulation layer thickness, the eccentricity of the vertical load in the outer wythe relative to the inner wythe has increased by 235%. It can be appreciated that, in instances where low U-values are required, the designer has to consider at an early stage whether to use a stronger connector system between the wythes to resist the eccentric forces or a thinner thermally more efficient (and probably more expensive) insulation to reduce these eccentric effects.

4.2 General Rules

Throughout the world, the design of structural concrete is now generally based on limit state theory. The ultimate limit state (ULS) of collapse has to be considered in all designs, and sandwich panels are no different to all other structural concrete members in this regard. Serviceability limit states (SLS) vary between elements depending on the application. For sandwich panels, special attention has to be given to thermal effects and more particularly to the differential temperature relationship between the constant environment of the inner wythe and the climatic fluctuations of the outer wythe. Panel sizes, layer makeup and chosen connection system are typically governed by these service effects.

There are many national building codes that can be used for the structural design of a sandwich panel. Example calculations are available in the Appendix to this document.

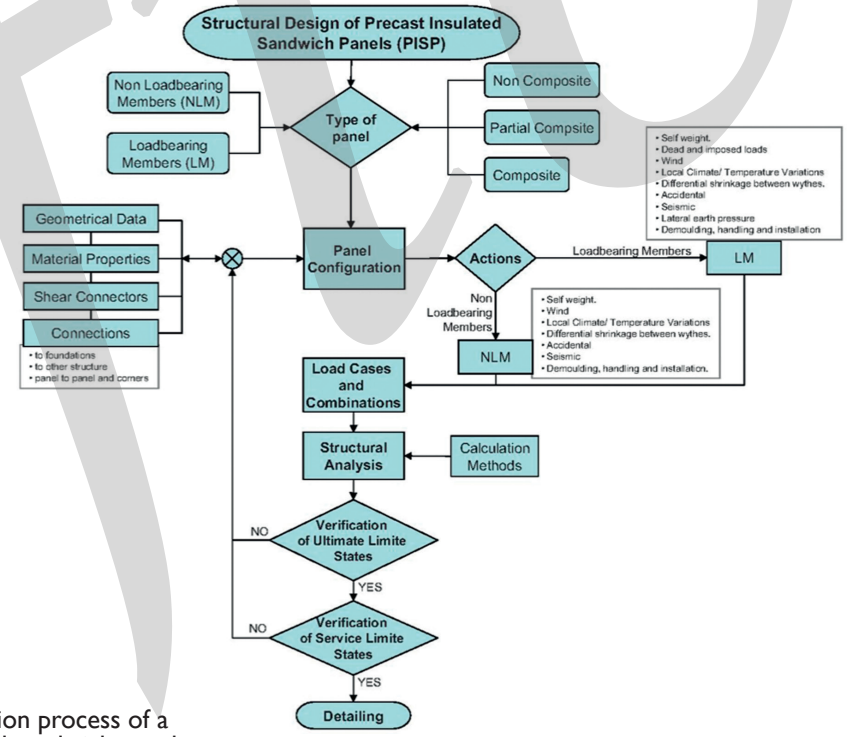


Fig. 4-2 Calculation process of a precast insulated sandwich panel

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4.3 Structural Behaviour

4.3.1 General

Precast sandwich panels can generally be categorised as either composite or non-composite members as defined in Chapter 2. There may also be intermediate categories of partially composite elements. For the purposes of describing structural behaviour, composite and non-composite cases shall be considered; these descriptions can be applied to the partially composite case depending on the degree of composite action that can be verified.

Figure 4-3 shows typical flexural stress and strain distributions for non-composite sections (a) and composite sections (b). These stress and strain distributions are idealised to facilitate calculation. There is no shear transfer across the insulation in (a), but in (b) shear transfer is required to distribute both stress and strain across the section. In this example, types of connectors that would be suitable for composite and non-composite sections are indicated. There are, however, many types of connectors available. These are covered more extensively later in this chapter. The connector type and arrangement chosen often governs the maximum panel size.

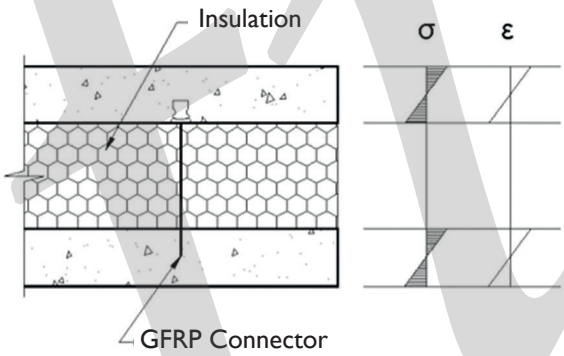


Fig. 4-3(a) Non-composite

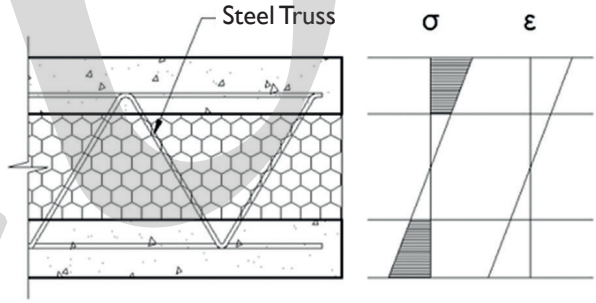


Fig. 4-3(b) Composite

It can be seen that the capability to provide composite action depends on the capacity of the connectors to transfer shear across the insulation. The connectors are therefore often categorised as either shear or non-shear connectors. A composite panel would predominantly have shear connectors whilst non-composite panel would mainly have non-shear connectors. However, the self-weight and any other actions applied to the outer wythe (such as wind) of a non-composite panel would still require shear connectors to transfer the forces to the structural wythe. The connectors transferring self-weight shear in the non-composite case are ideally located at the centroid of the sandwich panel or along orthogonal axes through the centroid to minimise thermal restraint and development of eccentric moments.

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4.3.2 Non-Composite Precast Insulated Sandwich Panels

The design of a non-composite sandwich panel is similar to a solid panel only if a single wythe is considered structural and the other wythe is non-structural. This simplifies the design approach and it is often the case for non-composite sandwich panels where the external wythe is made as thin as possible to minimise the self-weight of the panel carried by the connectors. The limitations on external wythe thickness are:

1. Achievement of reinforcement covers to satisfy durability and fire requirements;
2. Sufficient thickness for anchorage of wythe connectors;
3. Thickness based on the maximum aggregate size;
4. Architectural requirements;
5. Accommodation of false joints.

Subject to architectural constraints, the preferred minimum thickness of the external wythe is typically 65 mm. Some panels are produced with an external wythe of as thin as 50 mm, but careful attention to detail is required to satisfy the above-mentioned parameters.

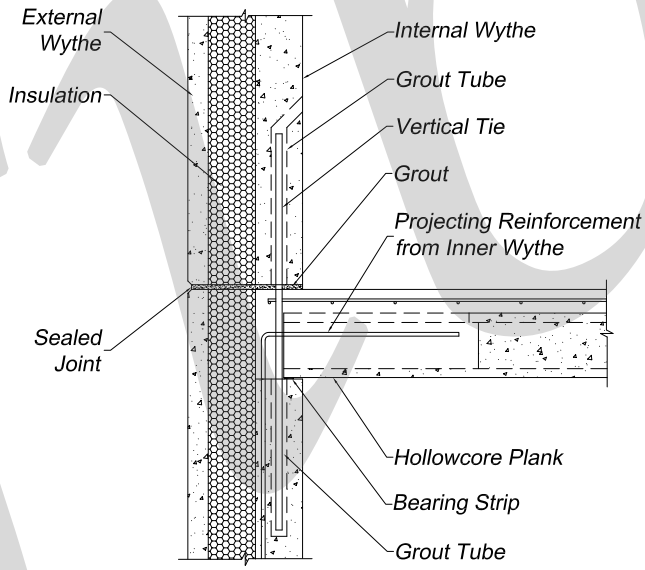


Fig. 4-4 Typical section of structural wythe supporting a floor unit

The thickness of the structural wythe is determined by structural analysis and the need to satisfy both structural and architectural details. Similar limitations as applied to the non-structural wythe also apply. Minimising the thickness of the structural wythe is often not economic as the amount of reinforcement required to limit deflection and cracking becomes excessive. In addition, where the structural wythe supports floors, the reinforcement connection and bearing details may dictate the inner wythe thickness as shown in Figure 4-4.

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In applications where there are both a structural internal wythe and a non-structural external wythe and the internal wythe supports the floor at each level, the internal wythe thickness is typically comprised between 150 and 200 mm, subject to the limitations described earlier. Where the sandwich panel is non-loadbearing, then the inner wythe thickness is typically 150 mm thick, but can be reduced provided that design requirements are satisfied. In countries such as Finland, inner wythes of 80 mm thickness have been used.

In flexural situations where both the internal and external wythes are considered structural in a non-composite panel then the loads can be distributed between them based on their relative structural stiffness and then each wythe is individually designed as a solid panel. Deflections are calculated based on the sum of the wythe stiffness. If the wythe's thickness is typically as suggested earlier, then the contribution from the outer wythe is relatively small and is often ignored, for example:

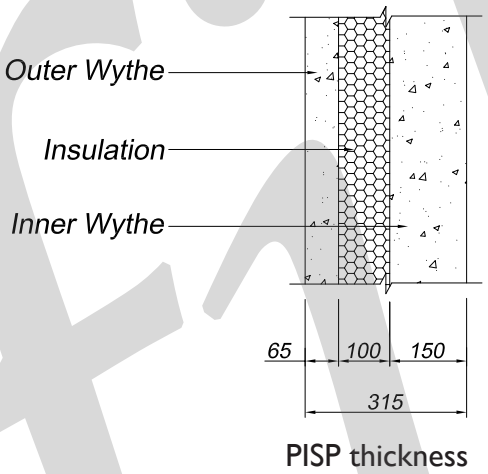


Fig. 4-5 Typical Sandwich Panel Cross Section

Outer wythe thickness:	Layer 1 =	65 mm
Inner wythe thickness:	Layer 3 =	150 mm
Insulation thickness:	Layer 2 =	100 mm
Total panel thickness:	Total =	315 mm

Second Moment of Area, Layer 1:

$$I_1 = \frac{1000 \cdot 65^3}{12} = 22.89 \cdot 10^6 mm^4 / m$$

Second Moment of Area, Layer 3:

$$I_3 = \frac{1000 \cdot 150^3}{12} = 281.25 \cdot 10^6 mm^4 / m$$

Proportion of load transferred to Layer 1 $= \frac{I_1}{I_1 + I_3} = 0.075$

Sum of wythe stiffness: $I_1 + I_3 = 304.14 \cdot 10^6 mm^4 / m = 1.08\, I_3$

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4.3.3 Composite and Partially Composite Precast Insulated Sandwich Panels

Composite and partially composite sandwich panels are popular in North America and are typically used in single storey buildings with large headroom requirements, such as warehouses and production facilities. The full section properties of the sandwich panel have to be mobilised to resist slenderness effects that would develop if treated as non-composite spanning vertically between ground and roof. The use of composite and partially composite sandwich panels in Europe is limited.



Fig. 4-6 Sandwich Panels may be Composite or Partially Composite

Composite and partially composite sandwich panels are those where inner and outer wythes are interconnected through the insulation by rigid ties or regions of solid concrete that restrict relative movement between the wythes. However, as energy conservation regulations are tightened and U-values for the building fabric are reduced, then the use of structural concrete thermal bridges through the insulation layer of sandwich panels will be limited. In North America, composite sandwich panels are often prestressed to further reduce section thicknesses and control bowing.

As many composite and partially composite sandwich panels are tall narrow elements spanning a single storey, flexure tends to dominate axial loading.

Flexural design of a fully composite sandwich panel is similar to that of solid panels that have the same cross sectional thickness but with the following differences:

1. A system for shear transfer between the wythes has to be provided and analysed;

2. Sandwich panel section properties have to take individual wythe thicknesses, the location of the composite centroid and the lack of concrete between the wythes into account.

The transferred shear force for connector design is calculated from the flexural tensile force and distributed between zero and maximum moment.

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Figure 4-7 below shows how composite section properties are derived:

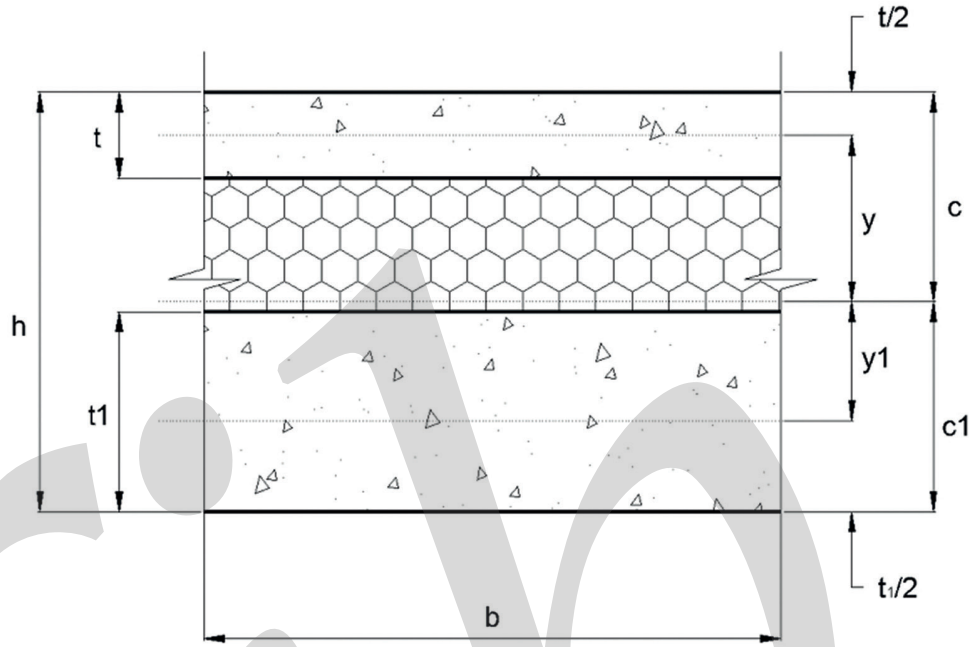


Fig. 4-7 Composite Section Properties

$$A = b(t + t_1)$$

$$c = \left[\frac{bt^2}{2} + bt_1(h - \frac{t_1}{2}) \right] / A$$

$$I = \frac{bt^3}{12} + bty^2 + \frac{bt_1^3}{12} + bt_1y_1^2$$

$$s = \frac{I}{c}$$

$$s_1 = \frac{I}{c_1}$$

$$r = \sqrt{\frac{I}{A}}$$

If we take our earlier example from 4.3.2:

t = 65 mm	t_1 = 150 mm	h = 315 mm	b = 1000 mm
c = 177 mm	c_1 = 138 mm	y = 145 mm	y_1 = 63 mm

A = 215,000 mm^2

I = 2,266.12 x 10^6 mm^4

S = 12.803 x 10^6 mm^3

S_1 = 16.421 x 10^6 mm^3

R = 103 mm

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If we compare the previous examples section properties with a non-composite sandwich panel with a single structural wythe, the wythe thickness then required for equivalent stiffness is 300 mm. The sandwich panels thickness would then become 465 mm, i.e. an increase of 150 mm in the overall panel thickness. The benefits of composite action for these applications is evident.



Fig. 4-8 Panel in production showing composite connectors

A recognised characteristic of composite and partially composite sandwich panels is the tendency of longer panels to bow outwards under prolonged exposure to heat. Bowing is a deflection caused by differential wythe shrinkage, thermal gradients through the sandwich panels section, differential modulus of elasticity between the wythes and creep from horizontal storage of the sandwich panels in a deflected profile. These actions cause one wythe to lengthen or shorten relative to the other. Compared to non-composite sandwich panels, the bowing of composite and partially composite panels is more pronounced due to the structural rigidity of the wythe connectors required for flexural strength and shear transfer.

Accurate estimation of the bowing amount is difficult due to the following reasons:

- Variance in shrinkage, creep and elastic modulus of the concrete;
- Prediction of thermal gradients and their shape through the sandwich panels;
- The degree of restraint provided by external connections;
- Difficulties in developing precise mathematical models for each of the above items.

Whilst there are some difficulties, the amount of bow can be accommodated in the design in a similar manner used to control precamber in prestressed beams and slabs. It is important to understand that bowing will occur and to establish a reasonable value for its magnitude, which may often be based on experience. Consideration must be given to external connections, so that distress does not occur because of forces that may arise.

Some useful observations have been made in relation to bowing of composite sandwich panels, and the following should be considered:

1. Sandwich panels generally bow outwards.
2. Panels heated by the afternoon sun will bow more than those that are not.
3. Sandwich panels bow daily due to transient thermal gradients.
4. Sandwich panels experience a greater thermal gradient than equivalent solid panels due to their superior insulation properties.
5. Panels stored with a deflected horizontal profile will keep that profile after installation.

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6. Differential shrinkage can occur between the wythes due to relative humidity differences between external and internal exposures.
7. Sandwich panels with wythes of different elastic moduli due to different concrete strengths, but with equal levels of prestress, may bow due to differential shortening and creep after prestress transfer.

In addition to individual panel effects, consideration must be given to differential bowing between adjacent panels. This can arise because of differences in structural stiffness, different connection levels or lengths, different shrinkage or creep characteristics due to being cast at different times, different storage conditions and particularly at corners where the adjoining panels will be bowed about orthogonal planes.

In comparison to composite sandwich panels, there is a lower tendency for a non-composite panel to develop thermal bowing. The extent of thermal bowing is chiefly influenced by:

- panel size,
- the rigidity of the wythe connectors,
- the degree of composite action and
- daily temperature variations on the external face of the panel.

In a non-composite sandwich panel, the internal wythe is typically kept at a constant temperature in a controlled building environment, whilst the external wythe experiences extremes of temperature, the thermal gradient through its section is minimal. The external wythe is free to expand and contract with variations in temperature.

In order to further minimise the effects of bowing, bond-breakers are often used at the interface of the insulation and the internal wythe. Polyethylene sheeting can also act as a vapour barrier as well as bond-breaker at this location. In addition, air gaps between the insulation and the outer wythe virtually eliminate bond between the wythes and allow for ventilation of the outer wythe, control of water ingress and pressure equalisation.

As it has been mentioned in Chapter 2, the degree of composite action of a partially composite panel should be declared in the design documents. This should be obtained by structural models validated by tests.

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4.4 Precast Insulated Sandwich Panel Applications

Sandwich panels can be either loadbearing or non-loadbearing members, and have a range of composite behaviour, as shown in Figure 4-9:

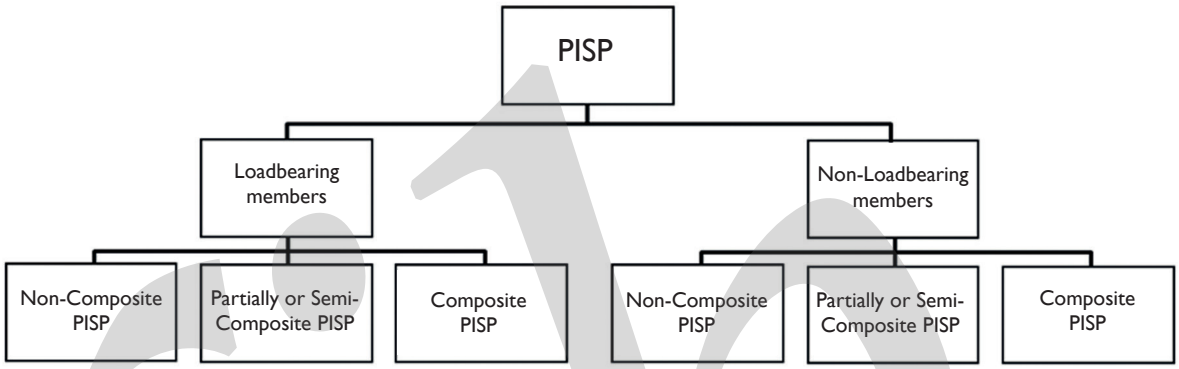


Fig. 4-9 Categories of Sandwich Panels (Where PISP = Precast Insulated Sandwich Panel)

Loadbearing members can have the full range of composite actions from fully composite to non-composite, and non-loadbearing members can have a similar range.

Loadbearing sandwich panels support loads from other parts of the structure, typically floors and roofs:



Fig. 4-10 Installation of Loadbearing Sandwich Panels

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Loadbearing non-composite panels are frequently used for multi-storey buildings with storey heights typically between 3.0 and 3.5 m. The connection detail with the floor often dictates the thickness of the inner wythe and the panel design is consequently not governed by flexure but by its axial capacity. Provided the effective height of the panel between floor restraints is less than about fifteen times the panel thickness for reinforced elements, slenderness effects due to axial load are minimal. The outer wythe is generally non-structural and is supported at each level by the inner wythe.



Fig. 4-11 Old Hall Street, Liverpool

An example of this type of application can be found on Old Hall Street, Liverpool, where a tower of twenty-seven storeys, 95 m high, was constructed in 2003. The external wythe of the sandwich panels incorporated white architectural concrete.

Multi-storey residential buildings are ideally suited for sandwich panels, particularly where cellular construction is a prerequisite, such as in apartment blocks and hotel construction. Grey precast concrete internal walling systems can be used in conjunction with sandwich panels, where these panels may have an architectural treatment.



Fig. 4-12 Internal Grey Walling System Ideal for Use with Architectural Sandwich Panels

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Various architectural outer wythe treatments are possible. Air cavities may be considered when using non-concrete or architectural concrete finishes as below in Figure 4-13:



Fig. 4-13 Close up image of the architectural off-white external layer, an air gap former, the layer of insulation and the internal structural layer

Non-loadbearing sandwich panels typically provide the external building shell and can be used with all types of supporting structural framing systems: precast and in situ concrete, and structural steelwork.

4.5 Wythe Design

4.5.1 General

Wythe thickness and reinforcement/prestress requirements are based on structural analysis and past experience, to resist the various design actions, finish, corrosion protection, and handling considerations.

Section 4.3 of this chapter examined the structural behaviour of composite and non-composite sandwich panels. This chapter reviews external actions applied to panels, how they affect loadbearing and non-loadbearing elements and the corresponding design approach.

4.5.2 Loadbearing Precast Insulated Sandwich Panels

Actions to be considered in structural design include:

- Self-weight;
- Dead and imposed loads from supported parts of the structure, particularly roof and floor loads, and supported sandwich panels above;
- Wind;
- Lateral earth pressure;

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- Local Climate;
- Differential shrinkage between wythes;
- Accidental;
- Seismic;
- Demoulding, handling and installation;
- Prestressing of the section.

Loadbearing elements in multi-storey residential and commercial construction, such as apartments, hotels, offices and some retail developments, have effective heights that are governed by the storey height of the building. Because the slenderness ratio is generally relatively low, there are no major benefits in prestressing the panels as slenderness effects and flexure are not critical, unless suited to the manufacturer's plant. The panels typically are, therefore, conventionally reinforced with the inner wythe acting as a structural member and the outer wythe as a non-structural member supported by the inner wythe. The wythe thickness and reinforcement content is generally determined from axial load considerations and connection requirements.

For low rise buildings up to three storeys with storey heights of between 3.0 and 3.5 m (i.e. houses and low rise offices and shops), loadbearing elements are also used in a similar manner as those for multi-storey buildings as above. In some instances, it may be desirable to stack the sandwich panels with both wythes bearing onto the foundation. The relatively thin outer wythe needs to be restrained by suitably designed connectors to the thicker inner wythe to limit slenderness.

Where storey heights are greater than those typically used for residential and commercial development, i.e. industrial, warehouse and general storage facilities, composite or partially composite loadbearing prestressed sandwich panels may be applicable.

There are systems where prestressed and reinforced panels are stacked and span horizontally between building columns, see Figure 4-14 below. Whilst in this example, the sandwich panels do not support the floor or roof, the bottom sandwich panels are supporting the panels above.



Fig. 4-14 Horizontal Sandwich Panels (Hollow Core Sandwich Panels – Insert)

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For buildings of this type, it is also common practice to use narrower, vertically spanning elements with prestressing in the longer direction as Figure 4-15 below.



Fig. 4-15 Vertical Panels

With relatively lightly loaded but long span prestressed elements, as used in high single-storey buildings, the serviceability limit state of cracking generally dictates the section size and prestress requirements. The design maximum crack width is dictated by durability and corrosion protection considerations and is limited in most standards for specified exposure classifications. In some standards, this is achieved by observing a maximum tensile stress in the outer concrete fibres that is related to the concrete cube or cylinder strength at various ages (Normally at transfer and at 28 days). Wythe section thickness and reinforcement cover requirements are also, in general, subject to fire protection requirements. These requirements are generally stated in standards as a fire rating that can vary from 30 minutes to four hours with prescribed minimum section size and reinforcement cover increasing as the fire rating increases.

For reinforced sections, cracking is generally limited through careful detailing relating to joint locations and reinforcement size and spacing, and control of service stresses in the reinforcement. Observance of good practice advised in most standards typically limits crack widths in reinforced members to about 0.3 mm. Lower design crack widths are achieved in more severe conditions through reduction in reinforcement service stresses by calculation, normally by either increasing reinforcement content, increasing wythe thickness or introducing prestressing.

External actions as listed at the start of this section are applied to the structure, and in turn the sandwich panels, in various combinations as advised in the applicable standard to achieve the most onerous design case. Thereafter, design section stresses are calculated to achieve the optimum section size and reinforcement/prestress requirement. Typically, dead, imposed, wind and soil loading are checked at ULS and SLS, and thermal and shrinkage effects at SLS only, with particular attention to thermal bowing. Further checks are carried out for accidental and seismic actions to ensure the general robustness of the structure and its member connections.

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As mentioned earlier, the sandwich panel section has to be designed for both ULS and SLS conditions. For prestressed long span members, it is likely that SLS conditions for cracking will dictate the finalised section. For reinforced members ULS, conditions should be adequate provided the limiting crack width achieved by the detailing rules is appropriate, where smaller crack widths are specified then SLS conditions may be more onerous. Sometimes, there are specified deflection limits outside normal requirements that may be critical, particularly where there are brittle finishes involved. Special fire and durability requirements may also drive the design.

An added benefit of loadbearing sandwich panels is that they can be used to stabilise the building frame as shear walls. As these elements will be transferring axial loads to the foundations, then adverse in plane moments resulting from application of horizontal loads from wind or seismic activity can be resisted by the beneficial moment from axial loading.

Sandwich panels can be idealised as acting as vertical cantilevers from the foundation. Horizontal loads transferred to each panel are calculated on the basis of the relative stiffness of each element in the stability group. Each panel can be treated as an individual shear wall in the group or can be connected to act integral with adjoining panels. If panels are connected to act integral with adjoining panels, large shears can develop at vertical joints requiring substantial connections.

Nevertheless, in cases where load bearing precast insulated sandwich panels are built in seismic areas, it is recommended that sandwich panels be connected to each other by means of vertical (and horizontal) joints that act integral with adjoining panels, since energy dissipation is expected to occur along the vertical connections (and partly along horizontal connections) of the loadbearing wythe of sandwich panel.

Provided the resultant eccentricity at any level in the shear wall is less than one sixth of the wall in plane length, no tension is developed and reinforcement content should not increase, minimum reinforcement or reinforcement required for robustness purposes would be adequate at horizontal joints. In cases where eccentricity is greater, an elastic load distribution is carried out and additional reinforcement is provided in tension zones to resist the design tensile force. Where there are transverse moments also acting, they would be combined with the axial force derived per unit length of wall from the elastic distribution and analysed as a column section subject to combined axial loading and uniaxial bending about its minor axis.

Generally, connections between sandwich panels and the adjoining structure should be adequately designed to transfer the design horizontal loads to the shear wall at each level of the building.

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Further information and guidance is provided in the following *fib* publications:

Bulletin 43: Structural connections for precast concrete buildings
Bulletin 63: Design of precast concrete structures against accidental actions
Bulletin 74: Planning and design handbook on precast building structures
Bulletin 78: Precast concrete buildings in seismic areas – practical aspects

4.5.3 Non-Loadbearing Sandwich Panels

Non-loadbearing sandwich panels are generally supported at each floor level and only resist the actions that are applied to its surface area. Care should be taken that additional load cannot be transferred to the non-loadbearing panel, for example through connections that may transfer seismic actions and through closure of joints with adjacent panels.

Actions to be considered in structural design are:

- Self-weight;
- Wind;
- Climatic temperature;
- Differential shrinkage between wythes;
- Accidental;
- Unintended seismic loading;
- Demoulding, handling and installation.

The design approach for non-loadbearing sandwich panels is similar to that previously explained in 4.5.2 for loadbearing sandwich panels except that the number of actions applied is reduced. In the case of shear walls, the structural efficiency of a non-loadbearing sandwich panels will be considerably reduced when compared to its loadbearing counterpart due to its reduced beneficial design axial load resulting from the absence of supported structure.

Non-loadbearing sandwich panels can be used with all structural frames as external cladding. A support is provided to transfer its self-weight to the structure and a lateral restraint is also provided to ensure stability. Normally, the vertical support is at the bottom of the inner wythe and the restraint at the top. The bottom support can be formed as a concrete corbel projecting from the face of the inner wythe or as a steel bracket bolted to the face of the wythe. The top restraint could be a proprietary steel bolt and anchor system, normally fixed to the underside of the adjacent upper floor or beam. There would ideally be two bottom supports and two top restraints per panel.

For non-loadbearing sandwich panels, normal structural requirements may not generally be critical as the vertical design loading is relatively small. It is common that practical considerations relating to handling, incorporation of lifting devices, support corbel details and fixing anchorages govern the wythe thicknesses. Minimum reinforcement is often adequate

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with localised strengthening at lifting and fixing locations. Prestressing would normally not be considered except for longer span elements.

4.6 Wythe Connectors

4.6.1 General

Wythe connectors are used to connect the outer and inner wythes together and keep the sandwich panel intact during its design life. They penetrate the insulation and are anchored in each wythe.

These connectors can take several forms and in the early days of sandwich panel, production would have been designed using reinforcing bars penetrating the insulation or solid concrete ribs bridging the insulation. Since then, various proprietary systems have developed. The present connector systems that are used fall into two main categories; metallic and non-metallic.

One of the main reasons for the development of non-metallic connectors is the widespread reduction in U-values allowed for walls and the need to avoid thermal bridging. Relative thermal conductivities are tabulated below for the main elements of a precast insulated sandwich panel.

GFRP composite, one of the materials used for non-metallic connectors, has more than two hundred times less conductivity than its steel counterpart. The benefits, when required to achieve low U values and high energy conservation, is evident. In addition, the tensile strength of the commonly used fibre composite connectors is about 800N/mm². However, the choice of connector type is often a commercial one, and non-metallic connectors must be priced competitively to make their choice viable against a comparable steel design.

Table 4-1: Conductivity of different materials

Material	λ Conductivity (W/mK)	Relative Conductivity
Expanded Polystyrene (EPS)	0.04	1
GFRP composite	0.30	7
Concrete	2.10	52
Stainless Steel	17.00	475
Mild or High Tensile steel	60.00	1500

In relation to metallic connectors, stainless steel is now generally recommended. Whilst galvanised steel has been used, any subsequent deformation can cause deterioration of the coating, and as the connectors are not accessible for inspection and maintenance there is a risk of long term corrosion.

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The connectors themselves are further subdivided into shear connectors, capable of transferring transverse shear forces, and non-shear connectors or ties that are less rigid and resist direct tension and compression forces only.

It is good practice that the wythe connectors should be designed to resist all the forces that are transferred between the two concrete wythes, independently of the insulation layer.

4.6.2 Shear Connectors

Shear connectors are used to transfer shear between the wythes. They can take a number of forms: they can be inclined legs or trusses, cylindrical metal or perforated plate. However, use of shear connectors, which are rigid by their design, can limit the maximum panel length through restraint to thermal movement of the outer wythe relative to the inner.

In composite sandwich panels, members are generally designed as one way spanning and shear connectors are stiff in one direction and flexible in the other. They also need to be continuous or evenly spaced in the rigid direction. Examples of these one-way shear connectors are shown below:

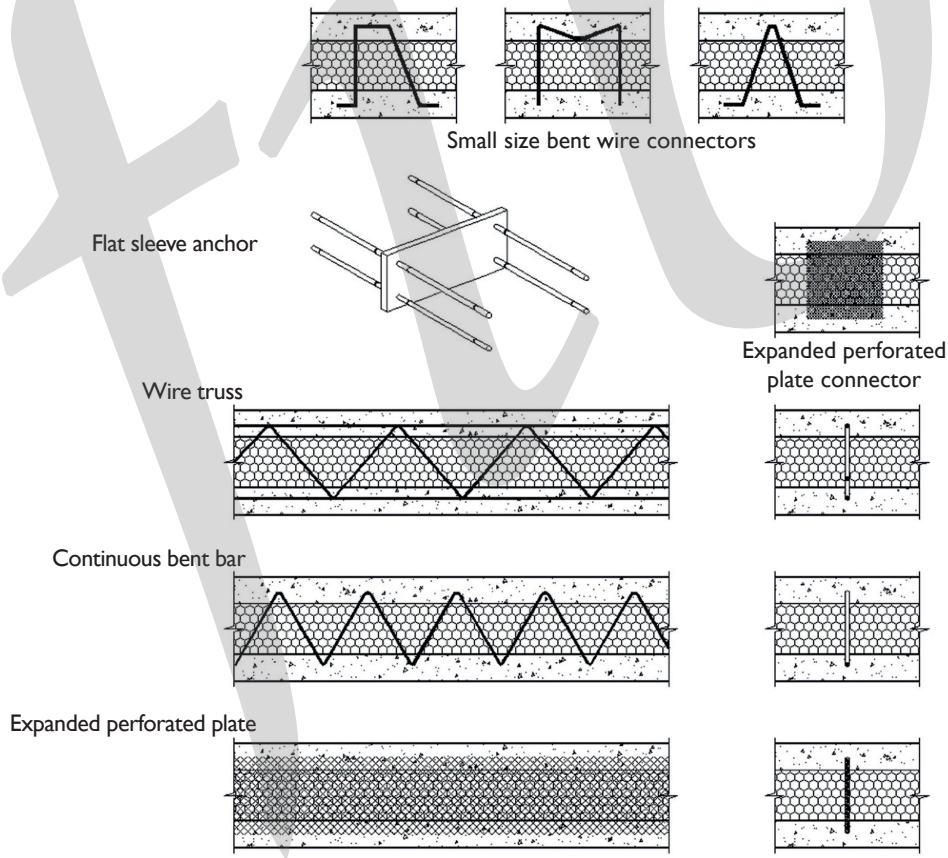


Fig. 4-16 Examples of One Way Shear Connectors

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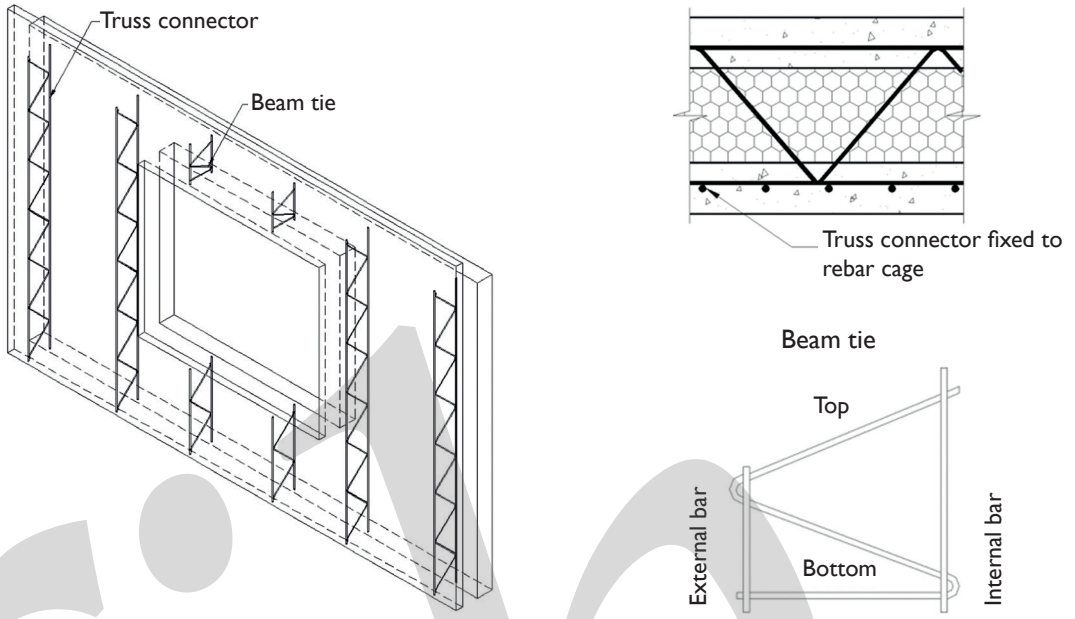


Fig. 4-17 Showing Truss Connectors, plus Beam Connectors over windows

The truss connector provides a means of shear transfer between the wythes and can be used to justify composite action. However, in low storey height applications (less than 3.5 m) the sandwich panel is often treated as non-composite with regard to flexural resistance with the inner wythe acting as the structural element. In the panel's structural design, the truss transfers the self-weight of the outer wythe to the inner structural wythe.

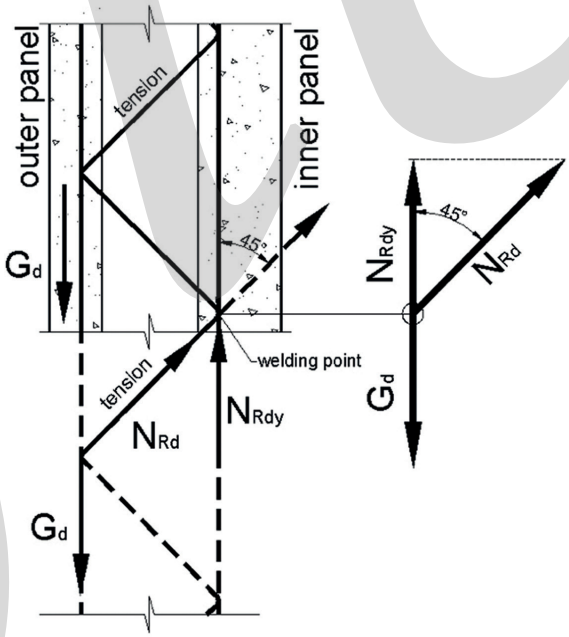


Fig. 4-18 Force distribution in truss connector (Typically truss connectors are used for thick insulation layers, greater than 100 mm, and may not be applicable to thin insulation layers)

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Shear connectors are required in non-composite sandwich panels to transfer the self-weight of the outer wythe to the inner wythe. Single point shear connectors, such as metal cylinders, should be located at the mass centre of the supported wythe. When this is not possible, added torsional forces need to be considered. In non-composite sandwich panels, shear connectors are often provided in pairs with each connector equally spaced on each side of the mass centre. As a rule, they act in a statically determinate system. A system with this arrangement is shown in Figure 4-19.

Capacities of shear connectors are obtained from connector suppliers. Software design packages are often available from suppliers that will design the connector types and layout for individual sandwich panels.

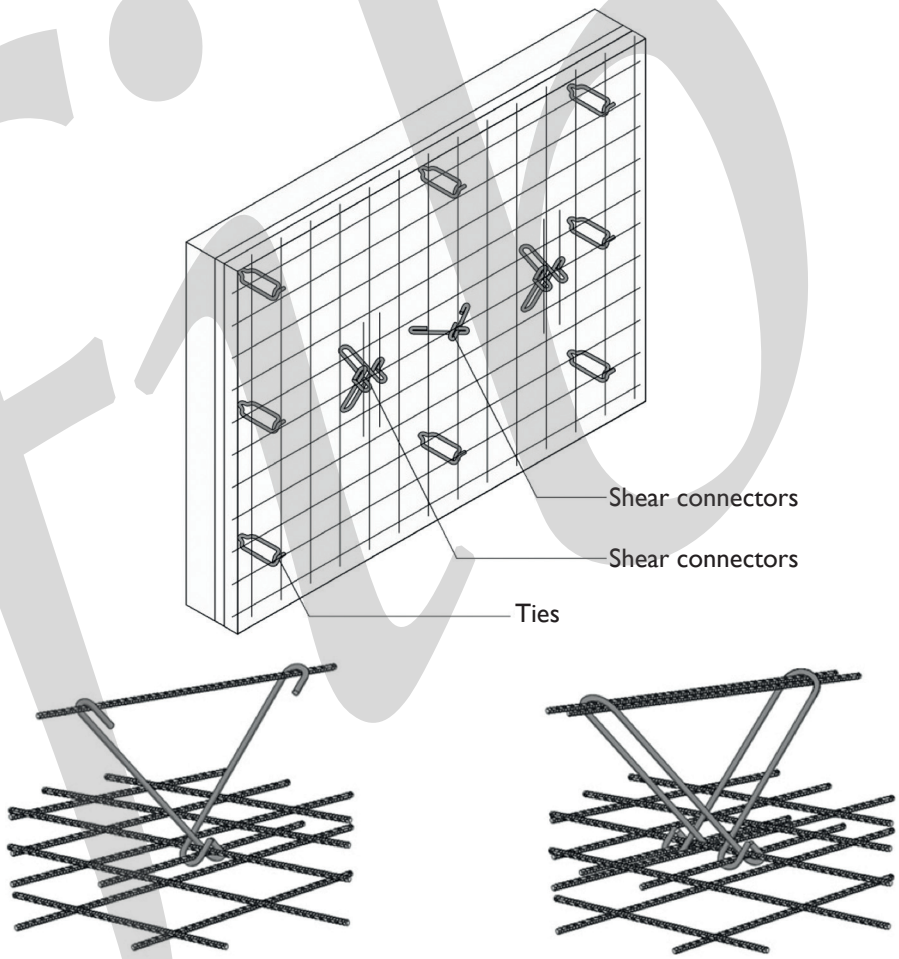


Fig. 4-19 Shear Connectors Near Centre of Mass in Non-Composite Sandwich Panels

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Fig. 4-20 Shear Connectors [Halfen GmbH]



Fig. 4-21 Shear Connectors [CPI Concrete Plant International]

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4.6.3 Non-Shear Connectors

In non-composite sandwich panels, the external wythe will move in response to environmental changes and concrete shrinkage. To accommodate this movement without damage, the connectors should be sufficiently flexible in the direction of movement so that undue restraint will not develop. As explained in 4.6.2, at least one shear connector, ideally located at the mass centre of the supported wythe, has to be provided to transfer the self-weight of the outer wythe to the inner wythe in the erected position of the sandwich panels. Tension and compression ties (non-shear connectors) are then distributed around the panel to transfer forces perpendicularly applied to the face of the outer wythe. These forces could be wind actions or those developed due to eccentricities. However, for some systems, both vertical and horizontal forces may be shared between all the connectors. The ties also act when the panel is handled in its horizontal position to transfer the self-weight of the lower wythe to the upper wythe.

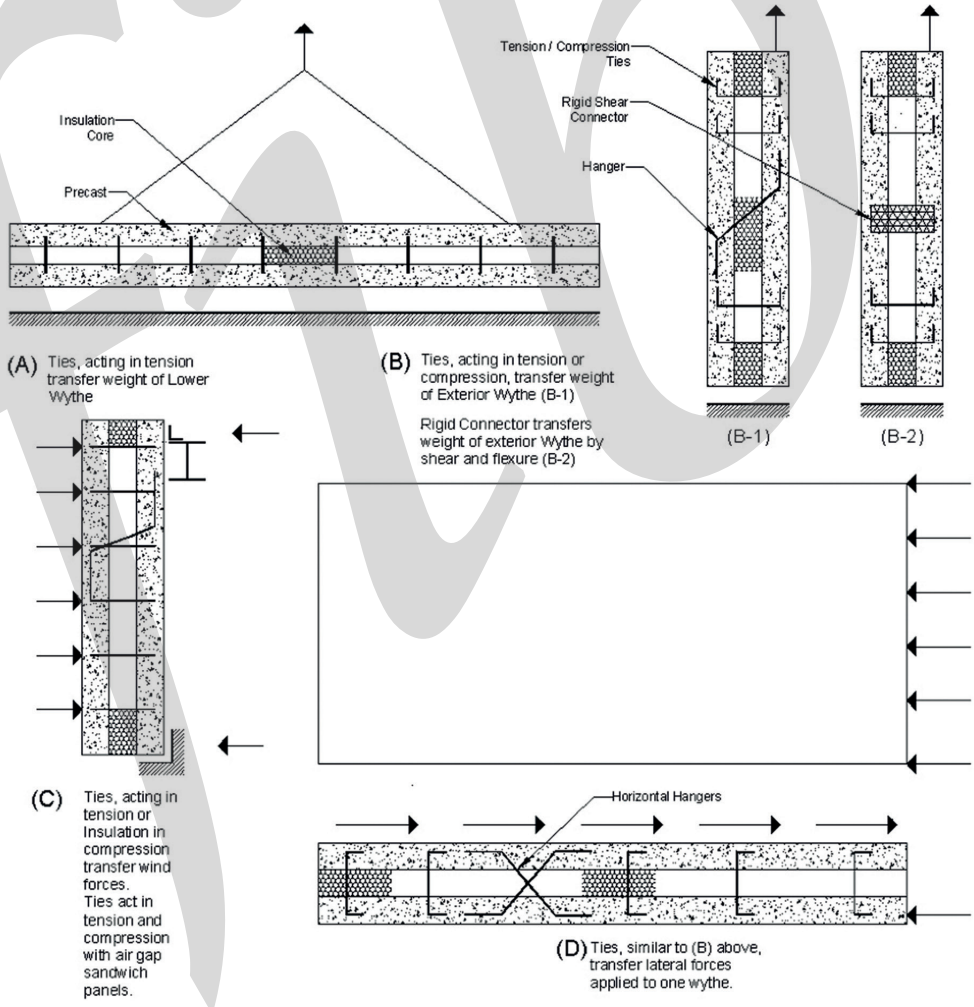


Fig. 4-22 Functions of Ties

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The ties used in the system in Figure 4-22 are illustrated below in Figure 4-23. Other types of ties are shown in Figure 4-24:



Fig. 4-23 Typical Tie System

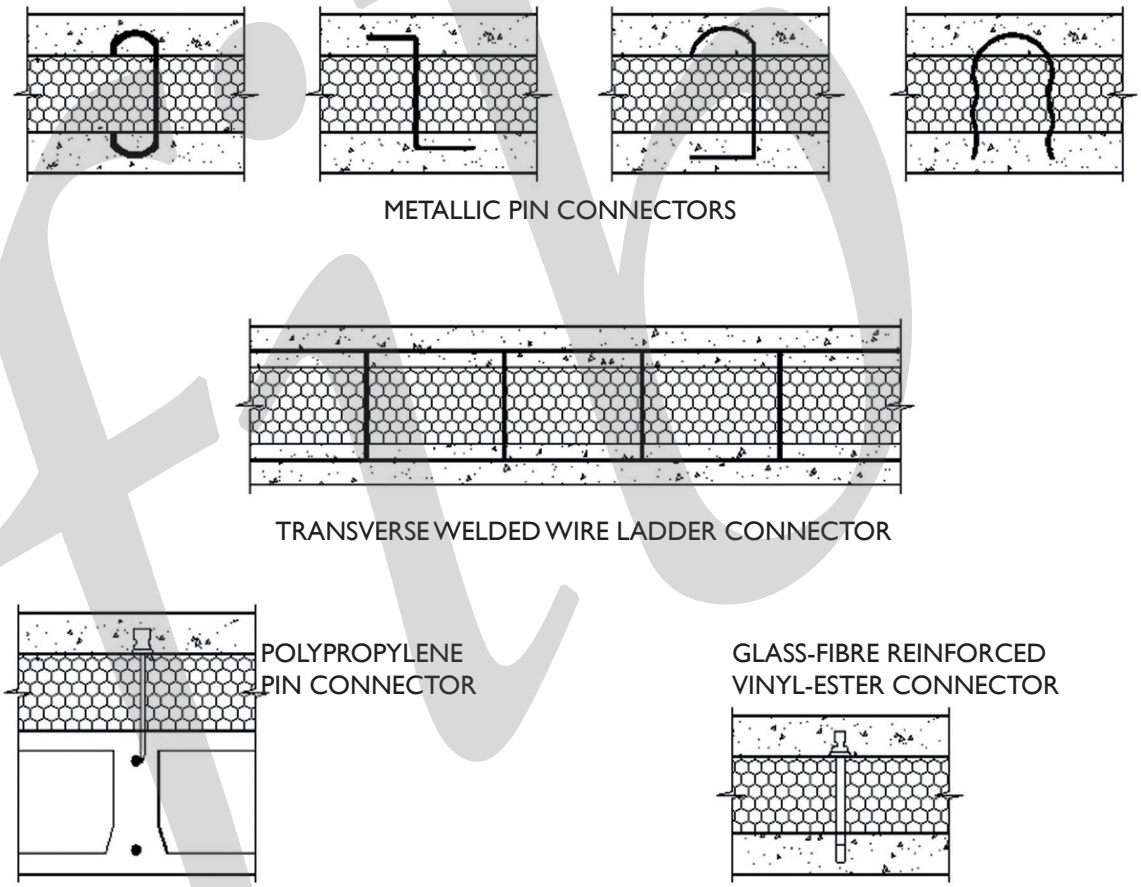


Fig. 4-24 Other Non-Shear Connectors

Tension/compression ties should be flexible enough so that significant resistance is not provided to temperature and shrinkage stresses in the direction parallel to the panel surface. They should have sufficient anchorage in each wythe to safely transfer the applied loads. To achieve this, the ties should be hooked around or tied to the wythe reinforcement, or their ends should be bent or deformed.

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4.7 Other Considerations

4.7.1 Joints

Sandwich panel to sandwich panel vertical and horizontal joints have to be designed to accommodate all calculated movements and tolerances and still remain waterproof and air tight.

When all the movements have been calculated, the joint width can be designed based on the movement accommodation factor, MAF, of the joint sealant. There must also be an allowance for the dimensional tolerance of the precast elements. An example (based on the terminology from the British Standard) of the calculation of joint width is given below for a multi-storey building where elastic shortening of columns due to axial loads has to be taken into account. The sandwich panels are supported by a structural frame and are therefore non-loadbearing and incorporate an architectural wythe:

Thermal movement
Light colour cladding temp range from -20° to +40 °C.
Temperature range = 60 °C
Panel height = 3.2 m
Coefficient of thermal expansion of limestone aggregate = 8×10^{-6} mm/°C
Thermal movement = $60 \times 3200 \times 8 \times 10^{-6}$ = 1.54 mm.

Elastic shortening of building columns
Provided by the project engineers as 1.00 mm.

Total Relevant Movement, TRM = 1.00 + 1.54 = 2.54 mm.

Movement capacity of the flexible sealant, MAF = 25% (From supplier's literature)

Minimum joint width, W min = TRM x 100/MAF + TRM= 2.54 x 100/25 + 2.54 = 12.7 mm

Panel manufacturing tolerance = ±5 mm

Minimum joint size = 12.7 + 5 = 17.7 mm

4.7.2 Fire

In general terms, the structural elements are fire protected for the following reasons:

- To allow occupants time to leave the building;
- To protect fire fighters;
- To protect the public from falling debris.

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National building regulations normally prescribe a fire rating to a building based on time, and related to its occupancy, purpose and height above or below ground level, to achieve the above-mentioned aims. Structural elements have to be designed to achieve that fire rating. In the case of structural concrete, this is achieved by satisfying minimum section thickness, cover to reinforcement, and minimum reinforcement percentage. It is the inner structural wythe that would be subject to stricter fire rating requirements, the outer wythe probably only rated for thirty minutes if considered non-structural.

The protection and fire resistance of both the insulation material and the behaviour of the connectors need to be assessed. Many product suppliers are able to provide suitable material test results to satisfy these requirements.

In addition, requirements for compartmenting the building have to be satisfied. In the case of sandwich panels, this means that each floor must be fire stopped where it meets an external wall (the sandwich panel) to prevent the spread of fire between separate building compartments. Careful attention must be given to the detail at this juncture to satisfy this requirement. The provision of air cavities alongside insulation needs to be carefully considered in relation to fire spread. The oxygen available in cavities can lead to accelerated melting of the insulation layer and connectors.

4.7.3 Durability

A durable structure has to be produced so that it can safely function during its design life under the exposure conditions that can be expected. The exposure conditions generally vary from mild or moderate for indoor conditions with constant temperature, to aggressive outdoor conditions where concrete can be directly exposed to salt attacks or other hazardous chemicals. Normally, for sandwich panels, it is the outer wythe that has the more onerous exposure condition. Generally, the outer wythe is subject to repeated wetting and drying cycles from rainfall and direct sunlight. However, if the elements are close to a highway, a car parking area or a coastal environment, then a more onerous category related to salt spray from vehicles may have to be considered.

Once an exposure class has been agreed for the sandwich panel, building standards typically relate the exposure class to concrete strength, mix parameters such as cement type, minimum cement content, water/cement ratio, and minimum cover to reinforcement. For an onerous exposure class, the thickness of the outer wythe could be affected.

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5 Manufacture of Sandwich Panels

5.1 General

This chapter will review the various production processes that may be adopted in the production of precast insulated sandwich panels. In general, the production process is very similar to the production process of an equivalent single layer (or solid) precast panel with the significant difference being the introduction of an additional internal insulating material.

5.2 Typical Production Process

These examples will briefly run through a typical manufacturing process in the production of a precast insulated sandwich panel. This process will vary depending on the nature of the sandwich panel: Loadbearing/non-loadbearing, composite/non-composite and any architectural treatment will all impact the casting process.

The production process for sandwich panels begins in a similar manner to single layer precast panels. The casting surface is prepared and side forms and openings are set-out. A noticeable difference with single layer panels at this point is the height of the formwork, which needs to accommodate the total depth of the panel.

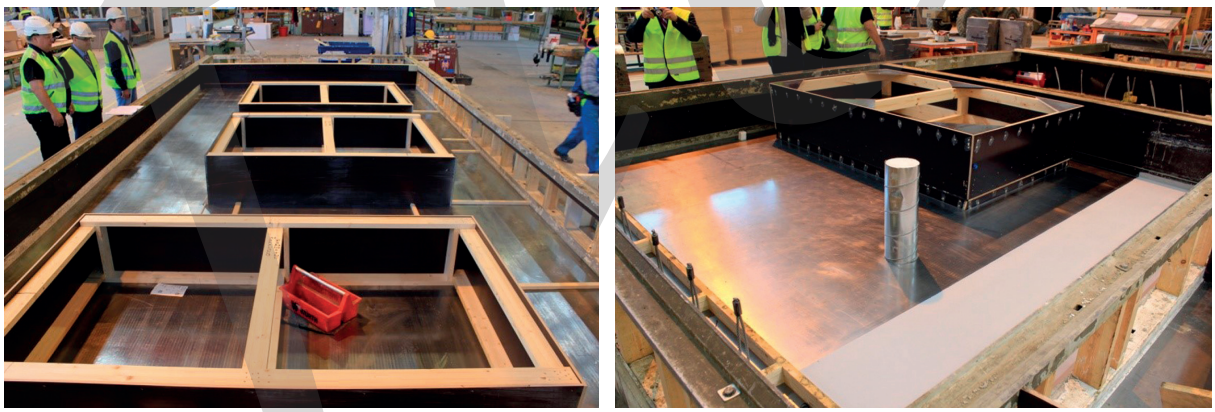


Fig. 5-1 Setting up Casting Table and Formwork

Once the formwork is prepared, the reinforcement is positioned for the first layer (off-form or table face) and the concrete is poured and levelled. During this stage, some connection systems, particularly composite systems, must be installed.

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For prestressed panels, the installation and stressing process must be incorporated into this first stage. Prestressing strands may be run through the panel and may require stressing prior to the installation of some connection systems.

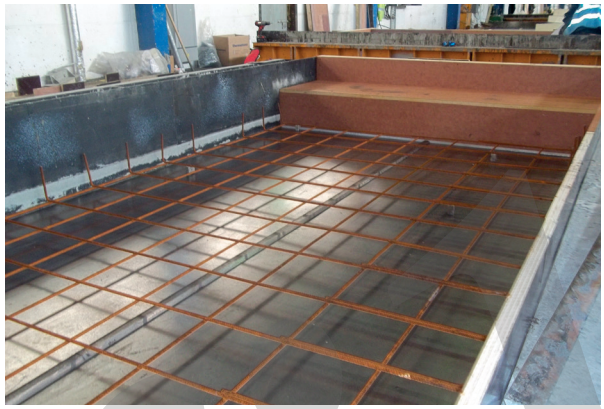



Fig. 5-2 Off-form layer, formed with reinforcement, ready to be poured

The insulation layer is then laid and the connectors installed in accordance with the manufacturer's and engineer's instructions.



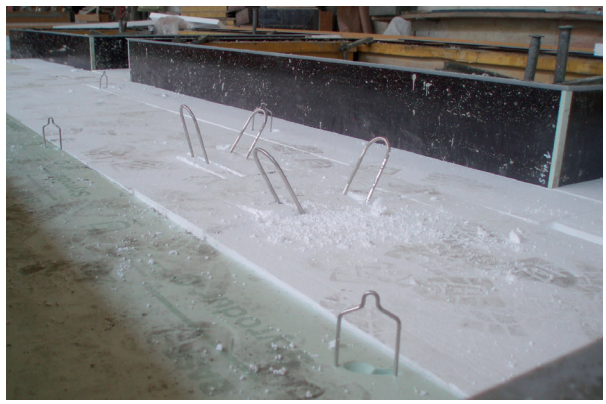


Fig. 5-3 Installation of the insulation layer (Note alternative connection systems)

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After the installation of the insulation and the connection system, the second concrete layer is prepared in accordance with the component shop drawings.

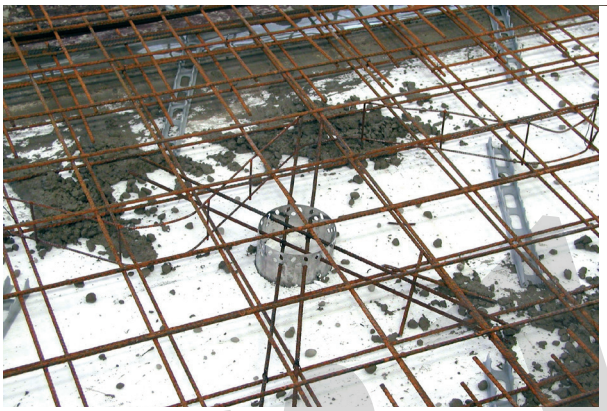
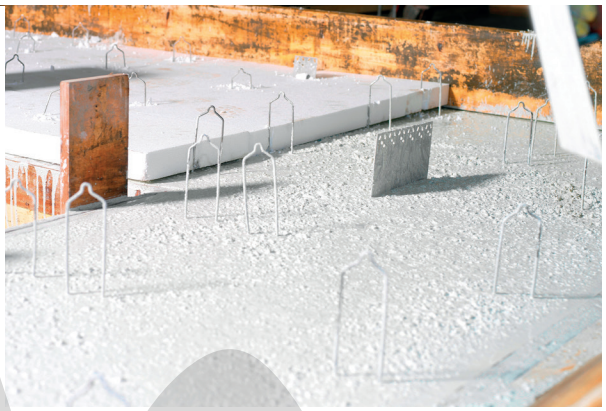



Fig. 5-4 Insulation layer installed along with the connectors and second layer reinforcement

It should be noted that the timing of the installation of the connection system between the two concrete layers is an important consideration. Once installed, the pins or ties shall be left undisturbed until the concrete has gained adequate strength. If the concrete is not left undisturbed there is a risk of impacting the pin anchorage.



Fig. 5-5 Top wythe prepared and ready for casting

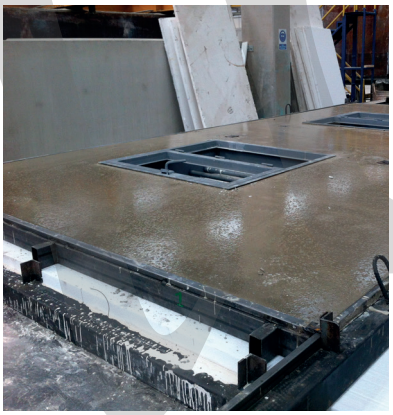


Fig. 5-6 Top wythe as cast



Fig. 5-7 Final finishing of the precast insulated sandwich panel

After curing, the lifting, handling and storage of sandwich panel is similar to that of a single layer precast panel. Consideration, however, must be given to the lifting positions and bearing points as they must be on the structural layer for non-composite panels.

Adhesion and form friction are assumed to act simultaneously during the lifting of the sandwich panel from the formwork. The action for demoulding situations affects the transport anchors as well as the shear connectors of the panel. In most cases, it is the lifting/demoulding loads that are the most critical for the shear anchors.

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Values for adhesion and form friction can be found in a number of sources, including [VDI/BV-BS 6205 Lifting inserts and lifting insert systems for precast concrete elements,VDI April 2012].

Table 5-1: Conductivity of different materials

Formwork, casting table conditions	**Adhesion (kN/m²)**
Oiled steel mould, oiled plastic coated plywood	≥ 1.0
Varnished wooden mould with panel boards	≥ 2.0
Rough wooden mould	≥ 3.0

The area to be used in the calculations is the total contact area between the concrete and the form. Structured, ribbed or 3-dimensional surfaces should be considered separately.

Note: The minimum values of this table are only valid if suitable measures to reduce adhesion and form friction are taken

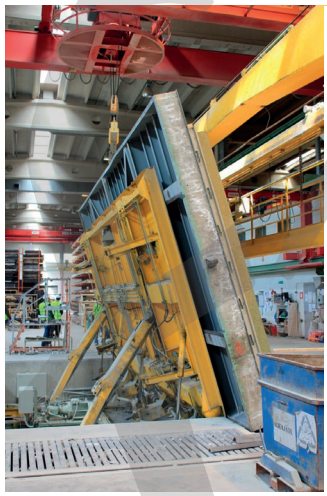


Fig. 5-8 Lifting of the competed precast sandwich panel



Fig. 5-9 Storage of the precast sandwich panel



Fig. 5-10 Precast sandwich panels prepared and ready for despatch

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Prior to despatch, it is important – while preparing the completed panel – to ensure that any residual concrete over the insulation layer is removed to reduce the possibility of thermal bridging.

Fig. 5-11: Check that there is no residual concrete covering the insulation layer.

5.3 Preparation of production and erection drawings

The shop drawing process is crucial to ensure the component is manufactured as intended in the project documentation.

The precast manufacturer prepares production and erection drawings for the precast insulated sandwich panels, complete with all necessary details for the fabrication, handling and erection of the precast elements. In order to do this, the manufacturer should have all applicable contract documents, including specifications, architectural, site and structural drawings. Erection drawings and hardware from other trades must be provided within contractual schedules. Detailing methods vary with the manufacturer; however, elevations and horizontal dimensions should be shown to locate and mark each precast element and give its relation to windows, openings, and adjacent building components. Details should provide size, shape, dimensions and profiles for each element. Connections, reinforcement, inserts, cast-in-plates, grout-tubes, individual mark numbers and, more importantly, the insulation and connection system must be clearly defined to ensure the finished product conforms to the project requirements.

The component shop drawings should indicate the type and thickness of insulation along with the type and details of the connectors to be adopted – including spacing and orientation of the connectors, embeds, reinforcing detail and additional details such as additional connectors or closer spacing around openings for elements such as windows and doors. The method of installing the connectors should also be considered during the preparation of the documentation.

During the shop drawing process, panel lifting and handling operations must be considered to ensure the safety of personnel and to minimise the potential for product damage.

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Erection drawings should show the following:

- proposed sequence of erection, if required;
- location and details of hardware embedded in or attached to the structural frame; and
- handling loads and additional reinforcement due to transportation and erection stresses.

Joint and joint sealant details should be shown where applicable. Furthermore, special fittings such as demoulding, lifting or erection inserts, anchoring details, reglets, cutouts, pipe sleeves, other embedded items and openings should be carefully detailed, located and dimensioned.

Drawings and calculations prepared to show the above should be forwarded to the client and the project consultants for approval.

5.4 Manufacturing Facilities

Facilities for the production of precast insulated sandwich panels vary widely. Production facilities will be affected by the size, weight, and volume of the products made and by the climate. The manufacturing facility should adequately provide the following:

- Facilities to receive and store raw materials such as cement, aggregates, reinforcing steel, insulation material and connectors, etc.
- Facilities for controlled proportioning and mixing of concrete, if required
- An area for manufacturing moulds and forms
- An area for assembly and fabrication of reinforcement
- An area for the casting operations, including space for the finishing and curing operations
- Adequate space for convenient and proper storage
- Equipment capable of lifting and handling components of the size and weight to be manufactured
- Facilities for prestressing, if required



Fig. 5-12 Example of a Precast Manufacturing Facility

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5.4.1 Formwork / Moulds

Timber, concrete, steel, plastics, plaster, polyester resins reinforced with glass fibres and combinations of these have all been used successfully as a mould or form material for precast insulated sandwich panels. Various patterns made of rubber, pressed metal, or vacuum-formed plastic may be combined with the basic materials for special effects. For complicated details, moulds of plaster, gelatin, or sculptured sand have been combined or reinforced with timber or steel, depending on the size of the components.

Steel moulds – Steel moulds are often selected for precast elements when it is anticipated that numerous assemblies and disassemblies of the mould will be required.

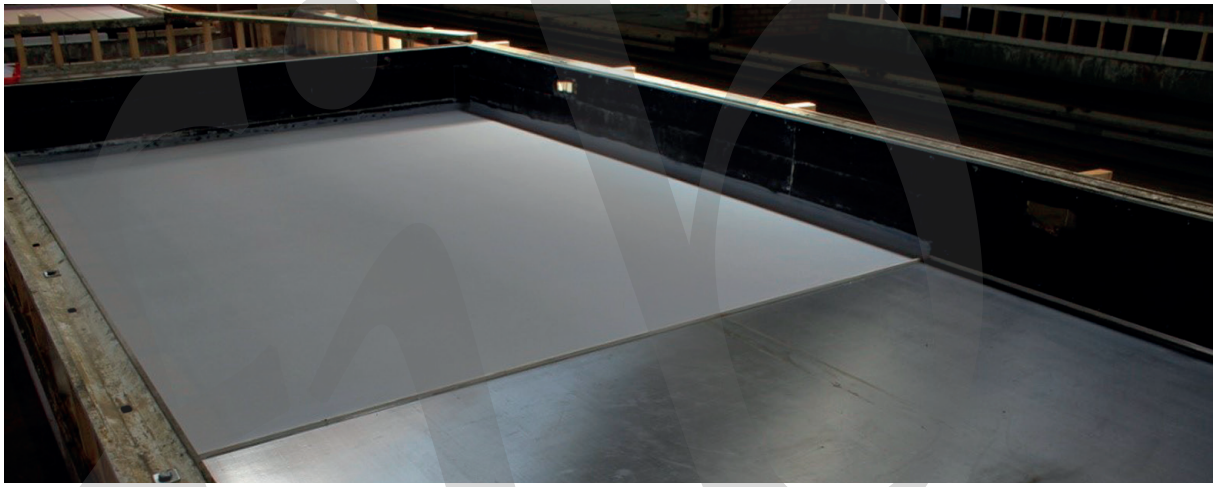


Fig. 5-13 Photo of a steel casting table with edge forms in place

Concrete moulds – Concrete can be formed into practically any shape and has excellent rigidity, dimensional stability, and the potential for a large number of reuses.

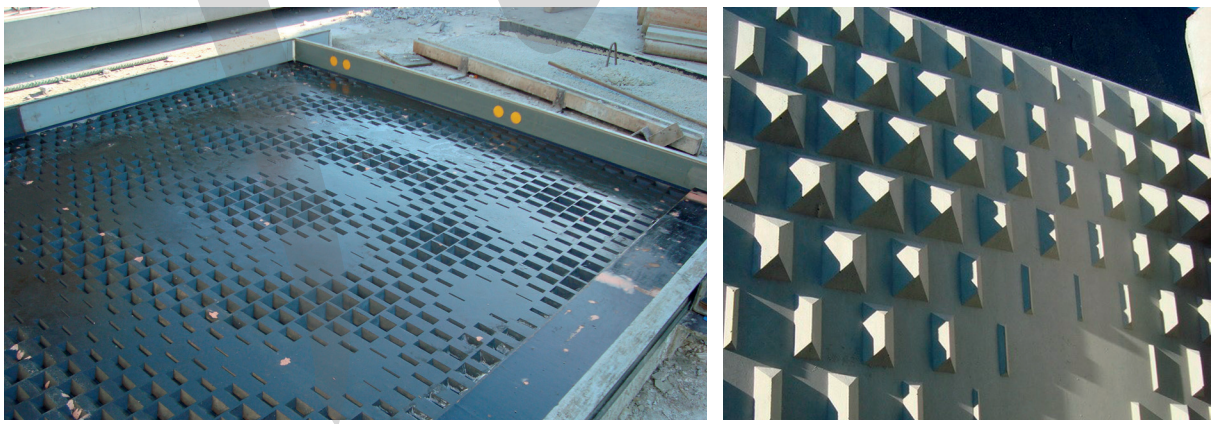


Fig. 5-14 Photo of a Concrete Mould and the resulting panel

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Timber moulds – Timber moulds vary from simple wooden moulds (particularly applicable when relatively small, flat panels are being produced) to elaborate, complicated moulds of unusual shapes and large dimensions.

Plastic moulds – Fibre-reinforced plastics produced from polyester or epoxy resins have considerable application because they can be easily moulded into complex shapes and can impart a great variety of patterns to the finished product.



Fig. 5-15 Photo brick pattern liner prior to casting

Form liners – Textures ranging from muted expression to bold relief are obtained with different types of form liners. Rubber matting is an effective liner, reproducing complex patterns faithfully on the concrete surface. While rubber is generally satisfactory, it should be tested for possible staining or discoloration of the concrete.

5.5 Reinforcement

5.5.1 Reinforcement cage assemblies

Reinforcement for precast insulated sandwich panels is usually preassembled into rigid cages or mats for each wythe using a template or jig before being placed in the form. Cage assemblies should be constructed to close tolerances, and the various pieces should be rigidly connected by tying or welding. Reinforcement cages should be securely suspended from the back of the moulds or suspended using bar-chairs and held clear of any exposed surface. The suspension system must firmly hold the assembly in its proper position during concrete placing and consolidation. Permanent spacers or chairs supported on the form of an exposed concrete surface may alter the appearance of the precast panel.



Fig. 5-16 Photo showing the upper wythe reinforcement being placed

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5.5.2 Prestressing

Precast insulated sandwich panels are sometimes prestressed to avoid cracks, to control warping or bowing, or to reinforce particularly large units. Firm anchorage of the pre-stressing steel in a prestressing bed or in suitably designed individual moulds is necessary. The concrete compressive strength when the prestressing force is released must be adequate to meet the design and handling requirements of the precast insulated sandwich panel. In the case of prestressed architectural panels, special attention should be paid to the transfer of the prestress force to the panel, particularly if it is a heavily sculptured panel or has many openings.

The accurate location of strands is important to avoid inducing permanent bowing or warping. Strand ends must be recessed and backfilled with epoxy or an appropriate grout, or otherwise carefully protected to avoid corrosion.

5.6 Concrete Placement

5.6.1 Transportation

Concrete for casting precast insulated sandwich panels is transported from the mixer and placed in forms by various methods depending on the precasting operation layout or the type of panel being manufactured. Many precasting plants have stationary mixers and deliver the concrete to the forms by buggies, buckets, conveyors, pumps or other equipment. Some precasting plants operate from a controlled ready-mixed concrete plant and transport the concrete by mixer trucks.



Fig. 5-17 Photo showing the upper wythe concrete being placed

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5.6.2 Segregation

The amount of segregation varies with the mix consistency and the aggregate grading. Secondary factors that may affect segregation are weather, as it affects consistency, and the mechanism of transportation. Equipment should be used that will provide the least amount of jarring and segregation from the time the concrete is placed in the transport carrier until it is delivered to the forms. Concrete must be discharged into the forms while in its original mixed or plastic state without separation of coarse aggregate and paste.

5.6.3 Consolidation

Concrete used in the manufacture of sandwich panels should be completely and uniformly consolidated by internal or external vibration, by vibrating screed, by impact, or by a combination of these methods. Although the available consolidation systems vary widely, most have been successful when properly applied.



Fig. 5-18 Photo showing the concrete being consolidated with a vibrating screed

External vibration - External vibration is usually achieved by mounting high frequency vibrators directly on the forms or by using a vibrating table. These vibrators operate at varying frequencies and amplitudes. Vibrating tables or forms should be sufficiently rigid to transmit the vibration uniformly over the entire surface of the panel without any form damage. A vibrating table works best for flat or low-profile units.

Internal vibration - Internal vibration is done with a tamping type motorised jitterbug or with a spud vibrator. Spud vibrators should not be used to consolidate architectural facing mixes.

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As backup mixes are generally thicker and stiffer, they can be placed and vibrated in the same way as regular structural concrete using internal vibration. Vibrators should not be allowed to touch the interior form surfaces, because contact will often damage the form or mark the concrete surface.

Drop-table vibration - Drop-table vibration is used in some precasting plants to consolidate concrete with a low total water content. The drop table rises and falls an average of 10 mm (3/8 in.) at a low frequency of approximately 260 cycles per minute.

At times, a combination of external and internal vibration is required to properly consolidate the concrete. When high slump concrete is placed, segregation may occur. With normal weight concrete materials, the coarse aggregate tends to settle to the bottom and the fines will rise to the top. With lightweight aggregates, the opposite occurs.

5.6.4 Facing concrete

Facing concrete should be carefully placed and worked into all parts of the form. This is particularly important in external and internal corners for true and sharp casting lines. Each batch of concrete should be placed as close as possible to its final position. The whole mass should be consolidated by vibration with as little lateral movement as possible. The thickness of a face mix after consolidation should be at least 25 mm (1 in.) or 1.5 times the maximum size of aggregate, whichever is larger. As a guide, the facing concrete should be thick enough to prevent any backup concrete from showing on the exposed face.

5.7 Surface Finishes

As precast insulated sandwich panels can be produced with either the external or internal layer being cast off-form (on the casting table), it is important to evaluate the most appropriate casting method. It is the architectural finish that will often dictate the casting orientation. If external decorative rebates, patterns, textured form-liner, exposed aggregate or a high grade off-form finish is required, then the panel would usually be cast with the external face off-form. However, if the external finish was to be honed or polished and consistent aggregate formation was required, or if a high grade internal finish was required the panel may be cast with the internal face off-form.

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Fig. 5-19 Project in Finland showing a combination of high quality off-form finish and inlayed tiles

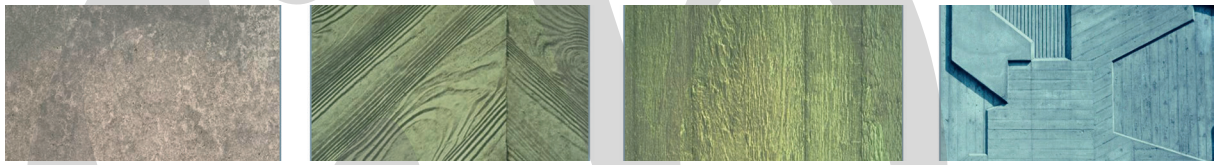


Fig. 5-20 Examples of 3 dimensional surfaces finishes



Fig. 5-21 Examples of external finishes that have been achieved using precast insulated sandwich panels

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5.7.1 General methods

When a precast insulated sandwich panel project reaches the fabrication stage, approval of both colour and texture will usually have been given. This is typically accomplished by nominating a specified finish, submitting a small sample, or in some cases producing a full size unit for approval from the client.

Surface finishes can be achieved in many ways, depending on the desired architectural effect. Surface treatments or finishes can be completed on either the plastic concrete or on hardened concrete. Finishes on plastic concrete generally use one of the following methods:

- Chemical surface retarders;
- Brooming, floating or troweling of the back face;
- Water washing and/or brushing;
- Special form finish;
- Sand casting;
- Surface texturing using formliners;
- Clay product veneer-faces;
- Stone veneer-faces.

Surface treatment of hardened concrete typically requires more labour and can at times be more susceptible to variations. Available methods include:

- Hand brushing and/or power rotary brushes;
- Acid etching;
- Sand or other abrasive blasting;
- Honing and polishing;
- Bushhammering or other mechanical tooling;
- Artificially created broken rib texture (hammered ribs or fractured fins).

Regardless of the type of finishing method, factors such as type of cement, aggregates, compressive strengths (at time of final architectural finishing), and curing techniques used will affect the final appearance. When finishes remove part of the surface of the concrete, the resulting panel must have adequate cover to the reinforcement at the completion of the surface treatment to prevent corrosion and staining. All methods of finishing must be studied for a project before entering into full production. The precast manufacturer must develop quality requirements for all architectural finishes before undertaking production of such finishes. The finishing process must produce an acceptable uniform appearance without loss of the required concrete qualities. When two or more different mixes or finishes are on the same panel, a demarcation (reveal) feature is necessary.

5.7.2 Chemical surface retarders

Chemical surface retarders are available in varying concentrations to control the depth of aggregate exposure. They may be used to treat the finished surface whether it is cast up or is on

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the bottom of the panel as cast. Retarders being considered for a project should be thoroughly evaluated under prevailing project conditions before production. The retarder selected should be compatible with the particular type and source of cement, aggregates, and specific mix selected for the panels. The effectiveness of surface retarders varies when the heat of hydration of the cement is altered. The heat of hydration may be altered by larger concrete masses, depth of precast product, changes in temperature and/or humidity, or by changing cements.



Fig. 5-22 High pressure washing to remove the surface retarder and cement matrix to produce the final exposed aggregate finish.

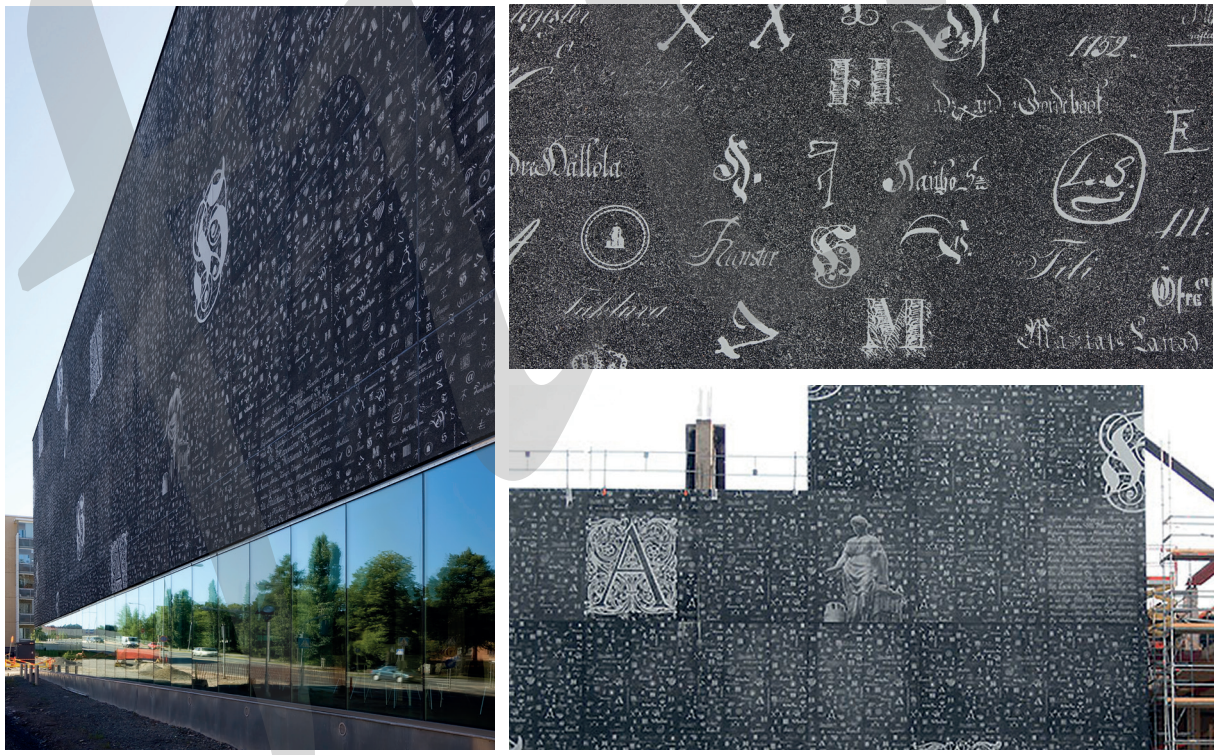


Fig. 5-23 A 'Graphic Concrete' surface finish achieved using surface retarders

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5.7.3 Abrasive blasting to expose aggregate

The age of concrete for abrasive blasting is not as critical as for other methods of exposing aggregates. Ideally, the concrete should not be more than about 3 to 5 days old, and all panels should have approximately the same compressive strength at the time of blasting. The concrete mix used and the compressive strength at time of abrasive blasting may affect the final exposure, as does the grading and hardness of the abrasive.

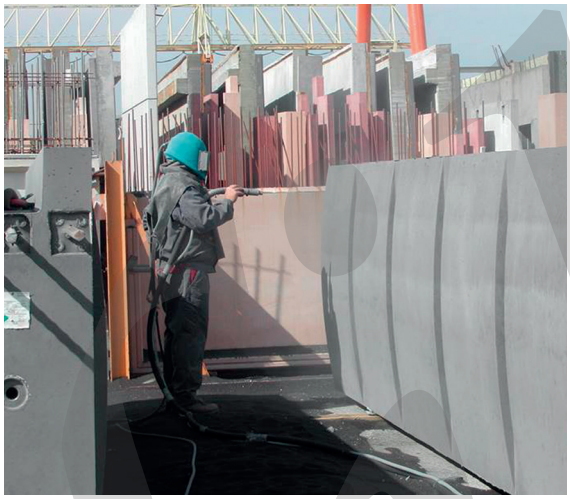


Fig. 5-24 Abrasive blasting to produce an exposed aggregate finish

The surface of large flat panels should be separated into smaller sections with rustication strips or by the use of ribs and form liners in order to minimise the visual perception of textural differences.

Materials used for blasting operations include; washed silica sand, certain hard angular sands, aluminium carbide, blasting grit such as power plant boiler slag, carbonised hydrocarbon, crushed chat, and various organic grits such as ground nut hulls and corncobs. Deep exposure of the coarse aggregate requires a finer gradation of abrasive to obtain uniform results. Tests with different abrasive materials with sample panels should be made to check the texture and colour tones.

Different degrees of exposure are:

a. Light exposure - where only the surface skin of cement and sand is removed, just sufficiently to expose the edges of the closest coarse aggregate.
b. Medium exposure - where a further removal of cement and sand has caused the coarse aggregate to visually appear approximately equal in area to the matrix.
c. Deep exposure - where cement and sand have been removed from the surface so that the coarse aggregate becomes the major surface feature.

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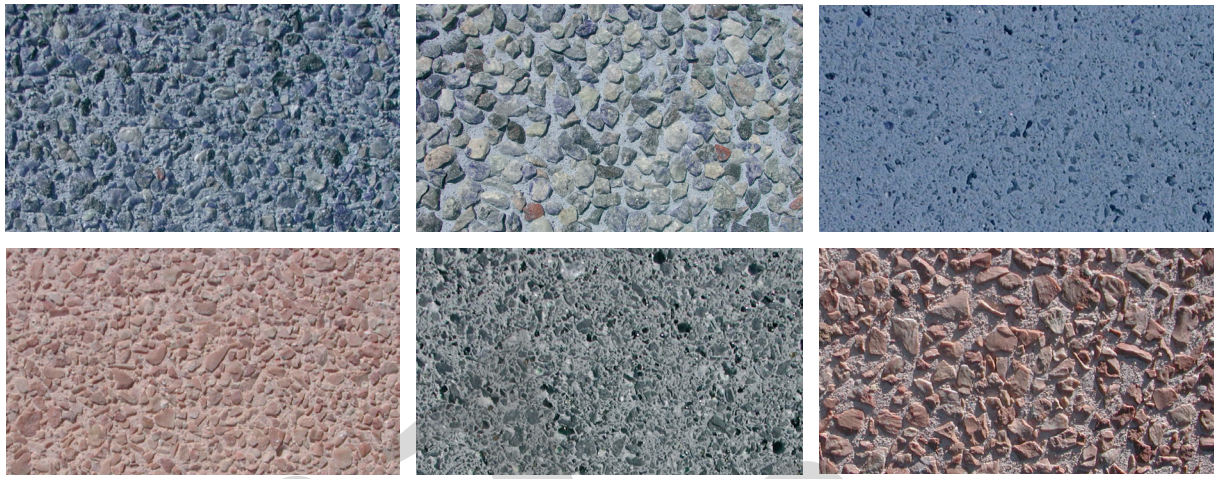


Fig. 5-25 Examples of the variation possible with abrasive blasting

5.7.4 Honing and polishing

Honing and polishing of surfaces provides a smooth exposed aggregate surface. Honing is generally accomplished by using grinding tools in stages, with successive degrees of grit fineness. Polishing can be done by continuing this grinding with finer grits. Generally, honing alone provides a sufficiently smooth surface for precast insulated sandwich panels.

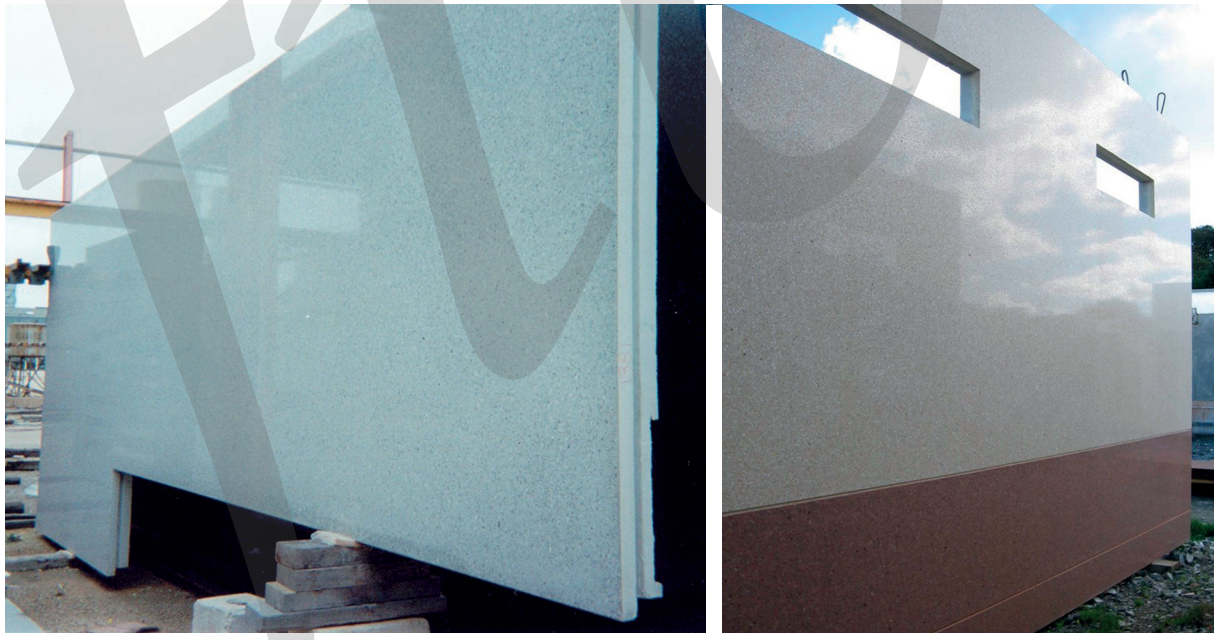


Fig. 5-26 Completed panels in storage

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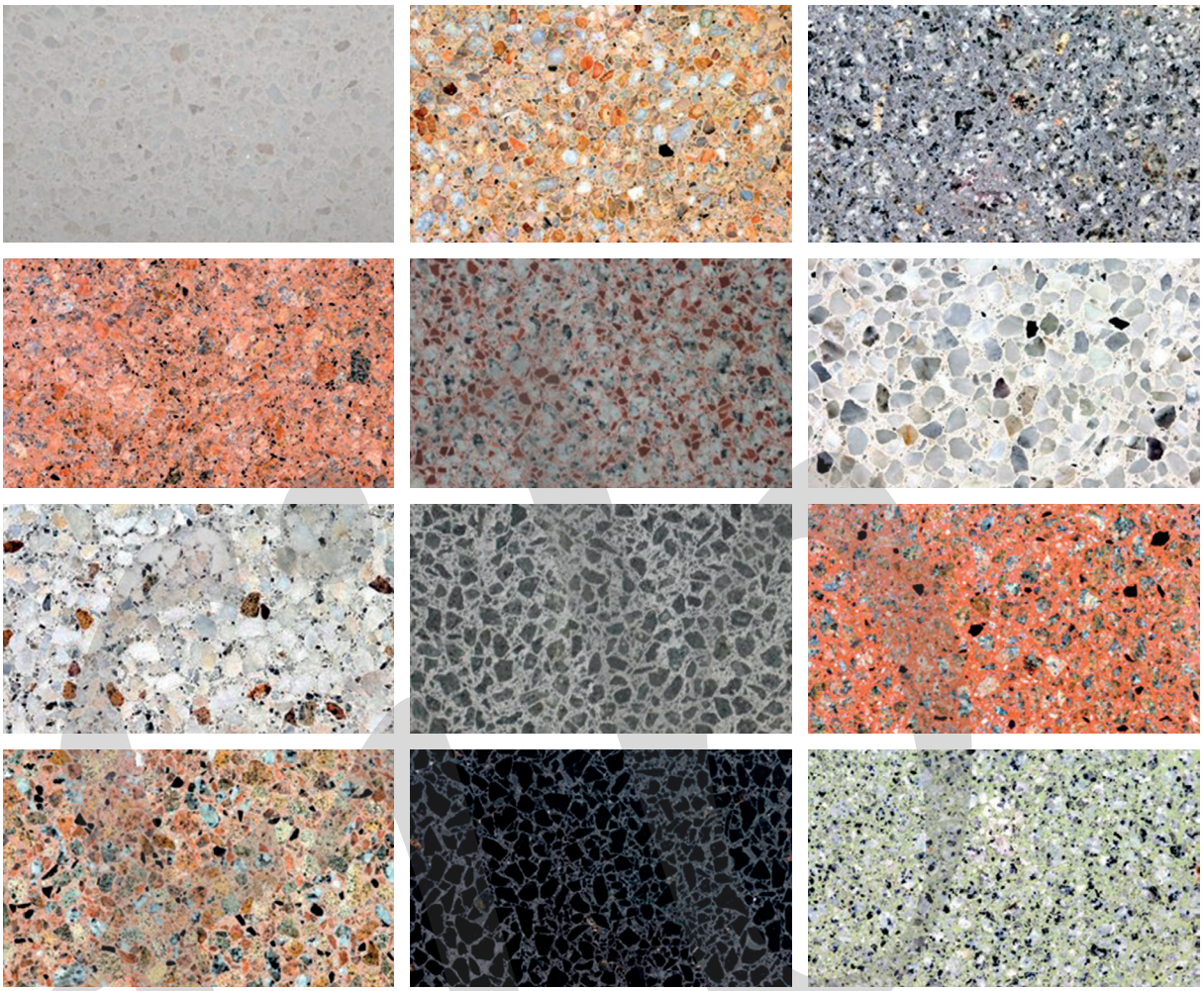


Fig. 5-27 Examples of various honed and polished surface finishes: shown with various aggregate colour and coloured pigment in the concrete mix

5.7.5 Acid etching

Due to the many types of aggregates used in architectural concrete, caution on the use of acids is in order. Before acid etching, a thorough study should be made of the effect of various concentrations of acid used for exposing aggregates or for the cleaning of panels. The concrete aggregates should be quartz, granite, or other acid resistant stone. Limestones, dolomites, and marbles will either dissolve or discolour when exposed to muriatic or hydrochloric acid. Acids may increase chemical reaction between silicates in the aggregate and the free lime liberated from the cement. This may lead to calcium silicate deposits on the panel surface if residue is allowed to harden on the surface. Acid washes may also damage the galvanising of exposed hardware and reinforcing bars if less than the recommended cover is used.

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Fig. 5-28 High pressure washing of the component to remove the acid solution

5.8 Concrete Curing

Curing of concrete takes place as long as sufficient moisture is present and favourable temperatures are maintained. In the manufacture of precast concrete, the initial curing usually takes place in the form. Secondary curing takes place after the product is removed from the form. Secondary curing may be less important in precast concrete because design strengths are established to enable the panels to resist maximum stresses usually occurring during demoulding and handling. Concrete mixes for precast insulated sandwich panels generally contain high-early-strength cement to assure adequate strength at demoulding (usually at least 20 MPa / 3000 psi). This strength often is achieved within 12 to 16 hours, while the precast panel is still in the form.

5.8.1 Curing recommendations

It is recommended that two different stages of curing be established for precast insulated sandwich panels. The first 16 to 20 hours is the initial stage and the most crucial. Steps should be taken during this period to both provide heat (if necessary to maintain minimum temperatures) and to prevent loss of moisture from the panel. The exposed portion of the fresh concrete should be covered during this initial phase.

After removal from the form, the secondary stage of curing should be continued until a compressive strength of 20-25 MPa (3000-3500 psi) has been attained. During this period, precast insulated sandwich panels should be protected from excessive moisture evaporation and from temperatures below 10°C.

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It may be necessary to interrupt the secondary curing to examine the surface finish and to do any required patching. It cannot be overemphasised, that curing at the early ages is extremely important to the strength and durability of the precast sandwich panel.

5.8.2 Curing techniques

Any changes in curing technique during a given production run may result in changes in colour, texture, or uniformity of the precast insulated sandwich panels. Therefore, curing procedures should be consistent and uniform from panel to panel as well as from day to day. Hessian or burlap and other similar coverings may cause staining or discoloration on certain finishes and should be avoided in these cases. Because of their tendency to discolour, curing compounds should be avoided, except on the backs of panels before the removal of forms, or on surfaces that will receive a finish later. Since some curing compounds and sealers may interfere with adhesion of surface coverings, coatings, and joint sealants, compatibility with these materials should be investigated.

5.9 Storage

Because of the wide variation in panel sizes and shapes as well as in the production facilities, there is no "standard" method for handling and storage. Precast insulated sandwich panels temporarily stored in a general storage area should be supported at the blocking points designated on the component shop drawings. Units should be stored in a vertical or near vertical position wherever possible. Handling and storage procedures selected should not cause structural damage, detrimental cracking, architectural impairment or permanent distortion when the precast panel is being:

(a) lifted or stripped from the mould;
(b) moved to various locations for further processing or storage;
(c) turned into various positions to provide access for finishing and/or surfacing operations:
(d) stored before delivery; and
(e) loaded onto delivery vehicles.

During storage, the manufacturer should keep the precast insulated sandwich panels in a clean, properly protected area to prevent staining. This does not mean the panels need to be in a covered area or must be covered. The need for protection will depend on the configuration of the units, the length of storage time, and the local environment. To protect against freezing damage, inserts and other embedded items should be protected against penetration of water or snow during cold weather. Storage must be planned carefully to ensure delivery and erection of the panels in an acceptable condition. Even though the panels may require washing after erection, protection may still be necessary against engine exhaust fumes or soil staining.

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Fig. 5-29 Photos of precast insulated sandwich panels in storage awaiting delivery



Fig. 5-30 Sandwich panels may be stored horizontally, however in most cases this should be avoided due to the additional stresses induced and greater risk of damage.

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6 Transport and Installation



Fig. 6-1 A new prison facility incorporating precast sandwich panels – during construction

6.1 General

Sandwich panel lengths and widths vary due to project requirements, form, size, handling equipment capabilities, transportation limitations, jobsite restrictions, and design limitations. Transportation restrictions vary worldwide and even vary within countries. In some areas, unescorted, permitted transportation of 3.6 m wide panels is allowed, but in other areas, this maximum width is only 3.0 m. Panels as wide as 4.6 m and as long as 23 m have been manufactured and transported.

Panels are handled in conformance with the design requirements.

Panels are either back-stripped, using standard lifting devices, special vacuum lifts, or edge-picked if cast on a special tilt table. Narrow panels may be handled using side-clamp lifting devices.

Demoulding design depends on the panels architectural features. Panel geometry allowing panels to be rotated on their sides (edge lift) generally will minimise cracking and allow panels to be stored on their edge in the yard. Edge storage will more easily allow exposed treatments to be administered.

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Flat demoulding may be necessary due to delicate contours of architectural features, thereby significantly reducing the potential for spalls and fracturing. Tilt tables are often used to rotate panels from the flat as-cast position to a side lift and storage position, or yard cranes may have two part lines and travel lifts may have two lift/hoist positions for panel rotation.

The fewer times a panel is handled, the lesser damage risk. Side lifts eliminate back face stripping anchors and are generally more economical.

6.2 Transport and Delivery

Precast insulated sandwich panels are typically shipped on edge, but may also be in the flat position. The transport position is dependent on equipment availability, form face, finish requirements, transportation equipment, and the flexural design of the panel. Prestressed panels will often permit flat position transporting more readily than non-prestressed panels.



Fig. 6-2 Panels being transported on their edge

When panels are transported on their edge, consideration of localised bearing stresses must be given to prevent chipping and spalling. Panels receiving special finish are often shipped on edge to prevent damage to the finish.

When panels are shipped in the flat position, more panels can usually be shipped per load. Some items that require attention include:

- Length of panel versus length of trailer. If the trailer is structurally flexible (such as a stretch trailer), over-stressing the panels may result from trailer twisting and deflection during transit;
- Dunnage is usually positioned at the lifting points;
- Care should be taken to ensure that the dunnage does not stain the panels;
- Jobsite access needs to be such that torsional twist of the trailer and panel is minimised.

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Fig. 6-3 Panels being prepared for lifting from transport

Most precast insulated sandwich panels are delivered on standard roads by semitrailer trucks as shown in Figure 6.2. A few are shipped by rail, barge, or other modes of transportation. Precast plant facilities do not generally restrict the size and weight of panels that can be produced. However, transporting oversize panels may greatly increase the cost of construction or delay completion of the project. Special permits are often required where height, width or weight exceeds specified limits. The use of lightweight aggregate concrete panels can, in many cases, minimise the impact of weight in transport, handling and erection operations. Travel may be restricted to good weather, daylight hours and weekdays. Equipment, such as lowboys, drop-decks or special trailers, may be required for large or heavy panels.

All precast insulated sandwich panels should be delivered to the site clearly marked as indicated on the erection drawings, with the date of production and an identifier that shows the final position of the unit in the structure. Precast insulated sandwich panels should be selected from storage, loaded, and delivered in the proper order to meet the predetermined erection sequence.

Before scheduling of delivery equipment, a field check of the project should be made by the erector to ensure that the site, foundations, walls and structure are in general, suitably constructed to receive precast insulated sandwich panels. The site should be checked for crane and delivery truck access, as well as possible field panel storage. Most panels are loaded vertically and supported on A-frames mounted to flat-bed trailers. They should be supported to minimise the effect of road shock and should be securely fastened with all contact points protected from damage. Corners and returns of unusual length should be braced from edge to edge for greater protection in transit. All material in contact with the panel should be non-staining.

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Generally, protective covering of a precast insulated sandwich panel during delivery should be determined by the manufacturer after considering such factors as size, shape, type of finish, type of aggregate, the method of transportation, type of vehicle, weather and road conditions, and haul distance. Since manufacturers are responsible for the condition of the delivered product, they make the decision to wrap the panel or not unless the engineer or the architect has specified a particular form of protection.

Economical panel sizes depend on the plant capability, distance to the jobsite, highway conditions, and transport as well as erection restrictions.

6.3 Planning and Preparation

Early in the construction, before panel manufacture, the panel fabricator, erector, engineer-architect, owner, and the general contractor should hold a coordination meeting to establish the working relationship, assure that handling techniques are satisfactory, establish the temporary erection bracing and establish mutually agreeable delivery schedules.

Access conditions at the site should be reviewed, considering temporary roads for delivery trucks and handling equipment such as cranes. Responsibility for sidewalks, overhead lines, barricades, truck space at site, sequences, coordination with other trades, and panel protection should be discussed at a project coordination meeting. At this coordination meeting, the precast erector should provide his scheme for the handling, loading, transportation and erection of the panels. Temporary bracing of the structure, on-site storage, connections, starting-location and sequence of erection relative to building stability should be discussed.

During the precast erection phase, the general contractor should conduct frequent project meetings between the erector and those subcontractors whose work is affected by the precast installation. These meetings will help to ensure that all necessary provisions have been made to facilitate the erection process.

The contract documents should clearly state any requirements or sequencing of erection needed to maintain building stability. Limitations on loading of the structure, temporary bracing requirements, or elevation sequencing need to be clearly shown before bidding. All details of temporary erection bracing, temporary connections, and shoring should be reviewed by the engineer-architect. The sequence of removal of any temporary erection connections should be shown, since leaving these connections in place can result in structural behaviour not intended by the engineer or the architect.

Before starting erection, bearing walls, foundations, structural frame, bearing surfaces, notches, embedded plates, angles or bolts, and welded connections should be checked for dimension,

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location, line, and grade to ensure that the area is ready to receive the panels. Any modification to bearing surfaces or connection hardware should be made by the contractor before erection begins. The precast erector should also check the access before scheduling the loading and handling equipment.

6.4 Panel Handling

6.4.1 General

Panel handling at the jobsite is generally the same as yard handling. Jobsite equipment availability and rigging must be considered during the panel design process.

Vertical panel storage is generally preferable in terms of yard space, damage risk, and positioning panels for loading. Care must be taken in locating storage points. Generally, storage points coincide with lifting points designated during panel design. Storage lateral supports must include considerations to minimise, or, hopefully, eliminate panel bowing in storage.

Bearing supports must be detailed to ensure that there is no crushing of the outer wythe of the sandwich panel.

Jobsite conditions, roadways, excavations, and the like, must be considered to eliminate torsion, which is twisting of the panels during access to the erection area. Handling diagrams are critical to safe panel handling and should be incorporated in the manufacturer's shop drawings and shop tickets by the precast concrete designer and made available to the erector.

Panels should be loaded and delivered in the erection sequence established at the project coordination meetings. Ideally panels should be lifted from the delivery trucks and placed directly in their proper position on the building. This minimises handling damage and is usually the most economical method.

Many requirements concerning the handling of panels at the fabrication plant, apply equally to jobsite activity.

The precast erector should set out joint location and spacing before actual panel installation. This should minimise differential variation in the panel joint width as well as identify problems caused by the building or the adjacent materials being out of dimension or alignment.

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6.4.2 Delivery sequence

A delivery sequence for panels should be sufficiently flexible to allow for:

- Full loads, using reasonable "fill-out" units if necessary;
- Control of unit position on the trailer with proper support for safety and economy;
- Adequate advance notice of shipment;
- Assurance of prompt unloading;
- Provision for some on-site storage.

If possible, panels should be unloaded by handling in a vertical position. This is usually the situation if single-story panels are shipped on frames in a vertical or an upright position. All chains, binders, banding, protective packing and bracing should be carefully removed from around the panels. Corners and panels with returns of unusual length are shipped with special bracing that should not be removed until the precast piece has been lifted slightly from the truck before installation. If belts are used in unloading, only one panel at a time should be removed. Protective material must be used between the belts and point of contact with the panel. Gangs of panels should not be removed with belt lifting devices unless the panels are palletised.

The exterior panel should always be unloaded first from a frame or a stack: never slide a panel out from the middle of a stack. Balance on the trailer should be maintained during unloading by unloading alternate sides of the vehicle. Remaining adjacent panels on the trailer should be tied or blocked to prevent tipping.

After delivery, a panel may require rotation into a new position; for example a tall panel delivered on its side must be rotated to a vertical position. A panel may also be delivered flat (horizontal) and then be lifted from the delivery vehicle and uprighted in the air. The panel is normally rotated without being allowed to touch the ground. It may be necessary to bolt a support frame to the panel before rotating. Usually two lifting lines from the crane are used, although special rotating frames have been developed for use with one crane line.



Fig. 6-4 Sandwich panel being lifting from transport

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6.4.3 Lifting devices

Lifting devices should be secured to panels in accordance with the lifting device manufacturer's recommendations. At least two lifting points should be used whenever the panel is lifted, so that the panel or the lifting line cannot spin and unscrew, causing the lifting line to become disconnected. Bolts of proper length must be used to ensure a full embedment in the lifting device. Regardless of the load requirements, a 19 mm (3/4 in.) bolt should be the minimum size used for any precast panel handling. Expansion bolts, predrilled or self-drilled anchors, should not be used for handling and erection purposes.



Occasionally, inserts, bolts, or other devices are provided only for the convenience of field handling. When these devices are located in finished edges or exposed surfaces, bolt and insert holes require filling and repairing. When this is necessary, the responsible engineer or architect should be advised so that the locations and repair procedure can be approved before panel fabrication. Repairs should be properly executed in accordance with Chapter 7.

Fig. 6-5 Installation of a panel requiring a fabricated lifting device due to site constraints.

6.5 Jobsite Storage

6.5.1 General

If the jobsite storage of precast insulated sandwich panels is necessary to meet the established schedule, the storage areas provided should be relatively level, firm, well drained and located where there is little chance of damage due to other construction activity. In addition, when long-term storage is necessary, panels should be covered to protect them from accumulation of dust, dirt, or other staining materials. Covers of canvas, rubberised sheets, heavy waterproof paper, reinforced plastic sheeting, or other protective material should be considered.

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Fig. 6-6 Photo of a project requiring job site storage

The storage area may have to be stabilised so that differential settlement or twisting of the stored panels will not occur. Panels should not be stored on frozen ground without proper safeguards to prevent uneven settlement if the ground thaws.

6.5.2 Panel support

Panels should be stored with identification marks clearly visible and supports at the blocking points shown on the erection drawings. Panels should be blocked to prevent tipping. When panels are placed against a frame or support, they should be set on protective material laid horizontally under or between the panels. This protective material should be selected so that the blocking material will not stain the panels.

Plastic chairs, chain guards, and bearing pads are readily available and do not stain. Wood blocking should be wrapped in plastic sheeting to avoid wood stains that can be serious enough to cause panel rejection. Polystyrene foam blocking may dissolve when the solvents of sealers touch it, leaving an unsightly patch of polystyrene that is virtually impossible to remove without defacing the panel. When solvent-based sealers are not used, polystyrene foam can provide good protection if it is of adequate size to support the imposed load.

6.5.3 Storage on a delivery vehicle

If jobsite storage is limited or of short duration, leaving the panels on the delivery truck is often more desirable, provided the shipper will permit extended truck usage. Leaving the panels on the truck provides a clean safe place and eliminates extra handling. This reduces possible damage caused by multiple handling and improper jobsite storage techniques.

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6.6 Panel Erection



The panel manufacturer should provide shop drawing details and must have preplanned erection techniques that are specific to the project. Consideration of cranes, rigging, and/or handling equipment is a must.

Fig. 6-7 Photo showing sandwich panels being installed

Precast concrete components must frequently be reoriented from the position used for transportation to their final in-service position. The analysis for this rotating operation is similar to that used during other handling stages.





Fig. 6-8 Architectural panels that require rotation from transport into their final orientation

The type of jobsite handling equipment selected may influence the erection sequence and affect the temporary bracing requirements. Several types of erection equipment are available, including truck-mounted and crawler mobile cranes, hydraulic cranes, tower cranes, monorail systems, derricks, and others.

When using two operating crane lines, the center of gravity of the panel must be located between the two lines in order to prevent a sudden shifting of the load while the panel is being rotated.

The capacities of lifting devices must be checked for the forces imposed during the demoulding operation because the directions and methods vary.

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Fig. 6-9 Photo of the installation of sandwich panels

6.6.1 Workmanship

Workers should be properly trained to handle and erect precast insulated sandwich panels.

Methods of erection should be planned to avoid soiling, cracking, chipping and damage to built-in items. Chipping and spalling may be repaired at the jobsite after installation, if done to the satisfaction of the engineer and the architect. For more information, please refer to Chapter 7.





Fig. 6-10 Installation of a brick-faced sandwich panel



Fig. 6-11 Once installed, braces shall be fitted and the panel secured prior to releasing the crane

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6.6.2 Equipment

Handling equipment for panel erection should be safe and reliable under all anticipated conditions to which it will be exposed. The equipment must not only accomplish the handling/erection quickly and economically but also eliminate any possibility of hazard to personnel on the site, to the public nearby, or to property. Factors involved in equipment selection include:

Mobility and cost – availability and cost of the handling equipment; cost of altering boom length or making other modifications; mobility needed for anticipated site conditions; whether the panels will be walked or carried;

Capacity required – the weights, dimensions, and lift radius of the heaviest and largest precast insulated sandwich panel; the maximum lift height and radius, and the weight to be handled at that elevation; the number and frequency of lifts;

Clearance needs – the clearance between the load and adequate headroom in which to operate; ground clearance and conditions of the ground on which to set the equipment; overhead clearance of wires and adjacent buildings.

The equipment selected must meet or exceed all project requirements and have at least a 5 percent working margin of reserve load capacity on every lift for unanticipated problems. When slings are used for panel erection, the included angle between the sling lines should never exceed 90° (or 45° from the vertical).

Lifting devices must be checked to assure that their capacity and intended use conforms to the manufacturer's recommendation. Panels should be handled only at the locations and with the hardware shown on the erection shop drawings. If slings are used, the panel should be marked so that the slings are placed in the proper location.

6.6.3 Bracing and guying

This section addresses the temporary bracing that may be necessary to maintain stability of a precast concrete structure during construction. When possible, the final connections should be used to provide at least part of the erection bracing, but additional bracing is sometimes required to resist all of the temporary loads. These temporary loads may include wind, seismic, or eccentric dead loads, which include construction loads or unbalanced conditions due to the erection sequence and incomplete connections.

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Temporary bracing is common in load-bearing sandwich panel erection and construction. Bracing must be a part of the sandwich panel analysis. Suppliers of bracing will assist in the availability of bracing design criteria. Bracing requirements should be established early so that proper allowances can be made. Necessary bracing and guying material should be delivered to the jobsite before erection begins. All bracing and guying methods must be designed to support all construction loads, including wind.



Fig. 6-12 Sandwich panel with bracing fitted for temporary stability

Building foundations, partial building slab placement, temporary strip footings, helical piers, or deadmen are used as foundations for the elements used to brace the precast insulated sandwich panels.

Building design should provide for structural stability during the erection of the panels. Until proper alignment and final connections are made, structural stability may not be achieved and bracing may be required.



Fig. 6-13 All temporary works need to be considered during building design.

When bracing/guying is used, the manufacturer's recommendations must be followed regarding load, length, and inclined angle. Special care must be given to the location, size and capacity of the insert in the panel, the propping pad, deadman or floor slab. Temporary bracing or guying should be arranged so that it does not interfere with other panels being erected, nor should removal of one brace remove support from the remaining panels.

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Fig. 6-14 Photo of braced sandwich panels

Removal of temporary bracing/guying should not take place until the building stability has been achieved through other means and authorised by the responsible engineer.

For most one-story and two-story structures that require simple bracing, steel-pipe braces similar to those shown in Figure 6-13 and 6-14 are used. Panel braces can resist both tension and compression. When long braces are used in compression, it may be necessary to provide additional lateral restraint to the brace to prevent buckling. Proper anchoring of the braces to the precast concrete components and deadmen (usually large blocks of concrete placed on the ground) must be considered. When the braces are in tension, there may be significant shear and tension loads applied to the fixings.

Properly designed deadmen that resist sliding and overturning are a requirement for safe bracing.

Cable guys with turnbuckles are often used for taller structures. Because wire rope used in cable guys can resist tension alone, they are usually used in combination with other cable guys in an opposite direction. A number of different types of wire rope are available. It should be noted that the capacity of these systems may be governed by the turnbuckle capacity.

Long cables will stretch due to imposed loads and temperature variations, which may necessitate a serviceability check if temporary deflections must be controlled. Compression struts, which may be the precast concrete components, are needed to complete truss action of the bracing system.

Careful planning of the erection sequence is important to ensure structural stability and safety during various stages of construction. Actual loads, factors of safety, equipment used, and the like must be evaluated for each project.

This sequence is usually dictated by the general contractor and requires coordination with the precast concrete erector, precast concrete production and transport departments, and the responsible engineer. A properly planned erection sequence can reduce bracing requirements. For example, with wall panel systems, a corner can be erected first so that immediate stability can be achieved. It is recommended that an erection sequence be established before precast concrete production begins so that multiple handling of components is minimised.

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Similar considerations for shear-wall structures can also reduce bracing requirements. All parties should be made aware of the necessity of closely following erection with the final diaphragm connections. This includes the diaphragm to shear-wall connections.

In order for precast concrete erection to flow smoothly, site access and preparation, the products to be erected, erection equipment, and bracing equipment including propping pads must all be ready, and the precast concrete transport must be planned.

6.6.4 Alignment

Offset lines are normally marked on the floors for multi-story buildings or on foundations for single-story buildings. Elevations for precast insulated sandwich panels are normally established by setting the properly sized shim pack on the floor or beam. Shim material should have adequate bearing capacity. Each panel should be erected to meet the appropriate tolerances, examples of these are shown in Chapter 7.

To hold overall building dimensions, it is necessary to work to joint centre lines, permitting the joint widths to vary. If a joint size is detailed as 12 mm (1/2 in.) and the panel tolerance is 3 mm (1/8 in.), the joint may vary from 9 mm to 15 mm (3/8 to 5/8 in.), provided approved connection and erection procedures are followed.

6.6.5 Bolted connections

Connections should be compatible with both precast and supporting frame tolerances, be simple in detail, and easily adjustable in the field to meet special project conditions. Connections should allow erection to proceed independent of ambient temperature without temporary protection measures. They should be as standardised as possible in order to minimise plant and field erection quality control problems. Once agreed upon by the engineer or the architect, the erector, and the precast supplier, the connections selected should be shown on the shop drawings submitted before panel fabrication.

Bolted connections are active immediately and allow for adjustment without tying up large handling equipment. Care must be taken during adjustment to prevent damage to either the panels or the adjacent building materials.

Standardised attachment hardware (clip angles, bolts, and shims) helps to minimise errors and control inventory. Regardless of the load requirements, a 12 mm (1/2 in.) diameter bolt should be the minimum size used. Clip angles should be slotted or have oversized holes to allow for product tolerances and building movement.

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6.6.6 Welded connections

Where welded connections are required, welding should be done in accordance with the relevant standards and in accordance with the erection drawings.

These drawings should show the type, size, length of weld, weld location and, if critical, the type of electrode. Panels may be shimmed while the initial tack welding is done.

Bracing or other provisions must be adequate to safely hold the panel in position while the handling equipment is released and adjacent panels are placed.

Before temporary bracing is released, the designated full weld should be in place at every connection in the panel. To minimise staining, all loose slag and debris should be removed immediately after the welding is complete. Panel finish and surrounding materials may require protection from sparks and smoke stain. Non-combustible shields should be used to protect exposed concrete surfaces during welding.

6.6.7 Post-tensioned connections

Post-tensioning, either vertical and/or horizontal, may be used for field connection of precast insulated sandwich panels using either bonded or unbonded tendons. Bonded tendons are installed in preformed voids or ducts; they are made monolithic with the member and protected from corrosion by grouting after the stressing operation is completed. The grout must fill all voids in and around the tendon for its entire length.

Unbonded tendons are connected to the panel only through the anchorage hardware. Anchorage devices for all post-tensioning systems must be aligned with the direction of the axis of the tendon at the point of attachment. Concrete surfaces against which the anchorage devices bear must be in the plane normal to the tendon direction. Post-tensioning operations require personnel, properly qualified and experienced with the stressing procedures and equipment to be used.

6.6.8 Dowels and grouting

The strength of a dowel connection in tension or shear depends on the embedded length and the developed bond. Since placement of a portland cement grout or epoxy grout is required during erection, use of dowel connections usually slows down the erection and may be costly.

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For doweled or grouted connections, setting shims are located and grout holes are filled just before setting precast insulated sandwich panels. The concrete in and adjacent to the grout holes should be damp or in a saturated surface dry condition.

Grout consistency should permit displacement of some grout when panels are placed in position. Where grout beds are required, the panels may be set on shims and dry-packed with mortar later. Panels may also be set onto fresh grout with the elevation controlled by shims.

Excess grout should be removed if it interferes with other construction activities. Use of epoxy and cementitious grouted connections should be avoided when the ambient temperature is below 5°C (40 F). Mixing and installation of epoxy grouts must be in strict accordance to the manufacturer's instructions. In selecting methods of doweling and grouting, consideration must be given to how the final joint will be made and how the corners will be joined. Adjustments to the precast insulated sandwich panels after the initial set of the grout may destroy the grout bond and reduce the connection strength. Doweled and grouted connections should only be used where they are part of the structural design concept.



Fig. 6-15 Lifting a precast insulated sandwich panel

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7 Inspection and Repair

7.1 General

For precast insulated sandwich panels, some of the essential characteristics for both loadbearing and non-loadbearing elements include the specified:

- Compressive strength of concrete and mechanical resistance;
- Ultimate tensile and yield strength of the reinforcing steel;
- Thermal resistance;
- Fire resistance;
- Acoustic performance;
- Quality of surfaces;
- Detail and geometric properties;
- Durability.

For external cladding panels particularly, there are specified demands for uniform appearance, surface consistency for both colour and texture. In addition, permeability and watertightness of joints is a critical requirement for many projects.

As such, the purpose of quality assurance systems and product inspection is to ensure that the manufactured precast unit fulfils all the project specifications and demands of the client and/or the end user during the whole life cycle.

7.2 Inspection at Manufacturing Plant

Many precasting plants have a quality assurance system or process. Some are ISO 9000 accredited (or similar), which means a competent third party organisation checks and certifies the quality control process. External sandwich panels are made of durable concrete mixes. Concrete (including raw materials), moulds, dimensional tolerances and reinforcement are controlled according to the national quality systems such as the PCI certification programme.

The main quality inspections for the components after manufacture are related to the completed concrete surfaces and are concerned with the evenness of the finished surface, colour variation and cracking. The most common imperfections on this type of component include: indentations, pores or honeycombing, protrusions or fins, loose concrete, surface waviness, nodes and cavities. Comparison of these imperfections with the specified surface classification enables the evaluation of acceptability of the finished component and the need for repair. See *fib* Bulletin 41: *Treatment of imperfections in precast structural elements*.

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7.3 Dimensional Tolerances

The allowed dimensional tolerances for precast elements are commonly divided into either structural or non-structural (compatibility) tolerances. Structural tolerances are, for example, dimensions of the cross-section and position and cover of the reinforcement. Non-structural tolerances are items such as the height of the panel or position of the window opening. For external sandwich panels and cladding panels, the non-structural deviations are often critical due to the aesthetic requirements of the project.

The dimensional tolerances are also divided into production, erection, and construction tolerances. Production tolerances are shown in standards and other technical documentation such as the PCI MNL-135-00, Tolerance Manual for Precast and Prestressed Concrete Construction. The following tables are given in European product standards:

Table 7-1 Tolerances of dimensions

Class	**Permitted deviation**				
	Basic dimensions				
	0 – 0,5 m	**0,5 m – 3m**	**> 3 m – 6 m**	**> 6 m – 10 m**	**> 10 m**
A	3 mm [a]	± 5 mm [a]	± 6 mm	± 8 mm	± 10 mm
B	8 mm	± 14 mm	± 16 mm	± 18 mm	± 20 mm
[a] ± 2 mm in the case of small claddings					

Table 7-2 Tolerance of positioning of openings and inserts

Class	**Permitted deviation**
A	± 10 mm
B	± 15 mm

Class B is most commonly adopted for precast sandwich panels, Class A is used when there is a requirement for more precise tolerances. Class A should not be considered as the norm, but as an exception finish only nominated for monumental structures or small areas of specific building that require an exceptional finish, also known as an architectural finish.

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Table 7-3 – Recommended tolerances for precast elements (Australia).

Tolerance classification	**Description**			**Acceptable deviation, mm**	
				Plus	**Minus**
Linear dimensions Tolerances in linear dimensions are illustrated in Figure 7-2	Dimensions of flat elements	Element length or width	< 3 m	3	3
			≥3 m < 6 m	6	6
			≥ 6 m	6	6
		Element thickness at any location		3	3
		Opening lengths or widths		3	3
	Dimensions of units other than flat elements	Cross-section overall dimensions	< 600 mm	3	3
			≥ 600 mm <1500 mm	6	6
			≥1500 mm	10	6
		Cross-section, dimensions of parts such as webs, ribs or flanges	≤1500 mm	6	6
			>1500 mm	10	6
		Length, critical dimensions of abutting members		0	6
		Length, non-critical	< 6 m per metre length	3	3
			≥ 6 m per metre length	6	6
	Features in all units	Diameter or side dimensions of core holes, ducts or similar		3	3
		Width or depth of grooves		2	2
		Location of grooves and fastenings for window frames, doorframes and similar features		3	3
		Location of grooves or strips for flashings		6	6
		Location of electrical outlets and similar features		12	12
		Other requirements		As specified*	As specified*
		Irregular curved or unusual shapes		As specified*	As specified*
		Position of individual connecting bolts, bolt holes, projecting metal or other devices in any associated group (e.g., the joint of two precast units), with respect to their position in the group		3	3
		Longitudinal location of any group of bolts, bolt holes, projecting metal or other devices, with respect of its true position in the unit in which the group is cast		6	6

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Angular dimensions Tolerances in angular dimensions are illustrated in Figure 7-3	Squareness of corners	Up to 2 m on shorter side	3	3
		Over 2 m, up to 4 m	5	5
		Over 4 m	6	6
Profile Tolerances in profile are illustrated in Figure 7-1	Straightness of edges and flatness of surfaces			
	Warp	Per metre width, in 3 m length	3	3
	Twist	Per metre width, in 3 m length	3	3

* As specified in the project documentation

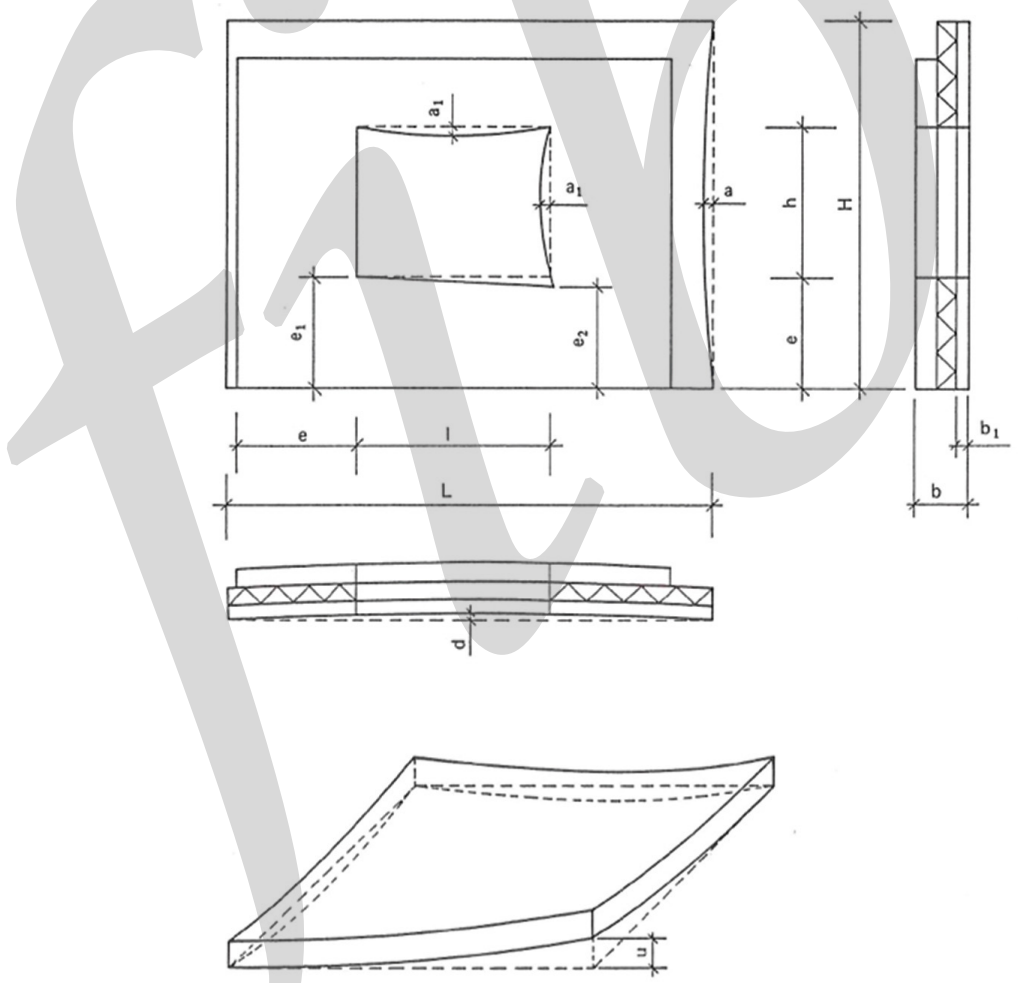


Fig. 7-1 Typical dimensional tolerances for wall panels

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NOTE: Out-of-squareness may affect measurement of tolerances in linear dimensions.

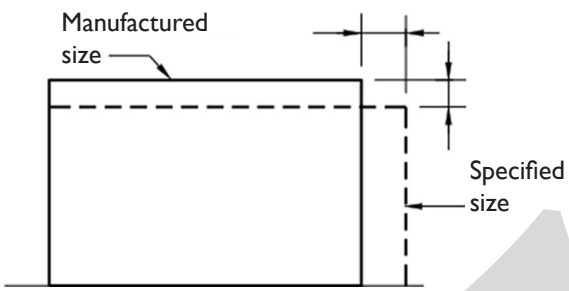


Fig. 7-2 Precast concrete tolerances in linear dimensions

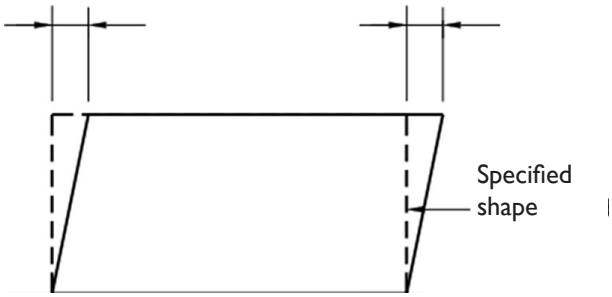
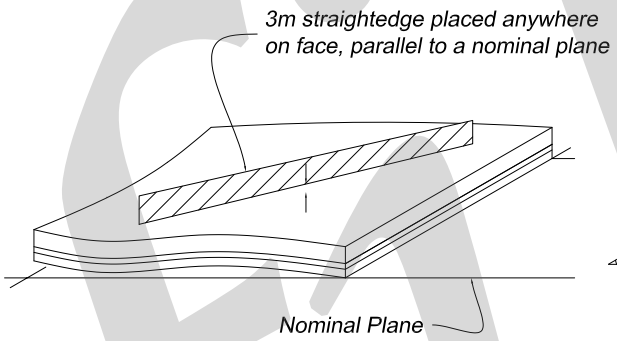
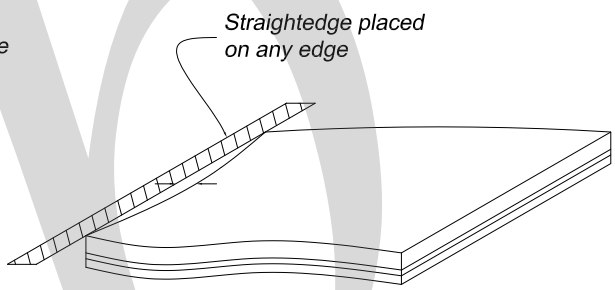


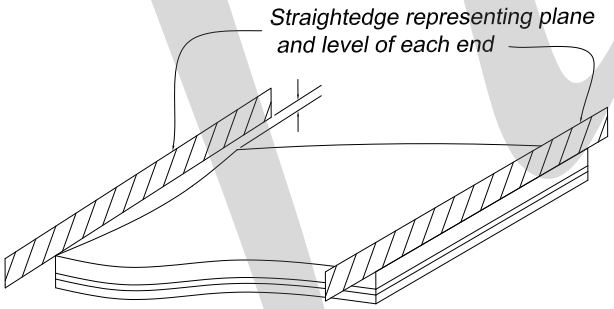
Fig. 7-3 Precast concrete tolerances in angular dimensions



(a) Measuring flatness



(b) Measuring straightness



(c) Measuring twist

Fig. 7-4 Precast concrete tolerances in profile

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Table 7-4 Insert tolerances from a specified position.

Type of insert	Acceptable deviation mm	
	Plus	Minus
Face lifting	20	20
Bracing	50	50
Strongback	5	5
Edge-lifting		
longitudinal	20	20
thickness	5	5
Fixing	5	5

7.4 Jobsite Inspection of Damage

In spite of the factory controlled conditions in which precast insulated sandwich panels are produced, they may still incur some imperfections during the manufacture, handling and storage. Components can also be damaged during the transportation and installation process.

The sandwich panels should ideally be checked prior to despatch; however, inspections should be carried out when the components arrive on site or at the latest before lifting them into their final position.

The surface finish of precast sandwich panels may have imperfections that may not meet the requirements of the project specification. The reason for these imperfections are often failures in the casting process, including; inadequate quality of the mould or casting surfaces, unsuitable form release agent or the incorrect use of concrete additives. These imperfections and possible repairs can be evaluated using *fib* Bulletin 41 where the following tables are shown.

1: Missing dowel bars or broken corners

2: Uneven support or failures at concrete surfaces

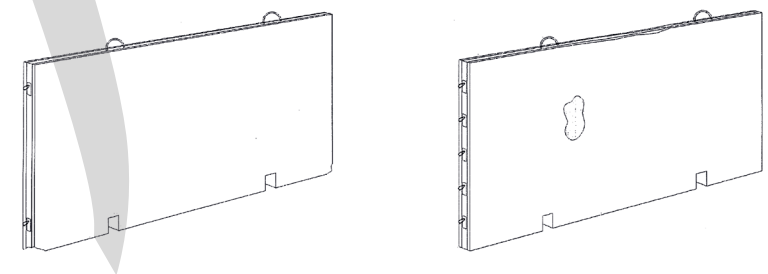
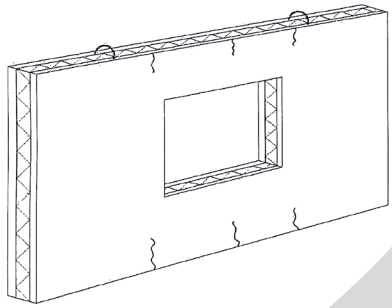


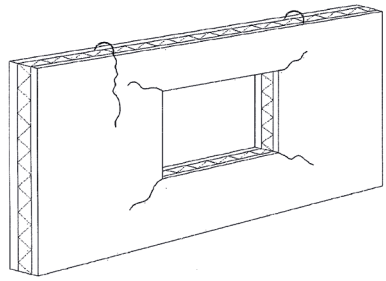
Fig. 7-5 Imperfections of loadbearing walls and sandwich panels (adapted from the *fib* Bulletin 41).

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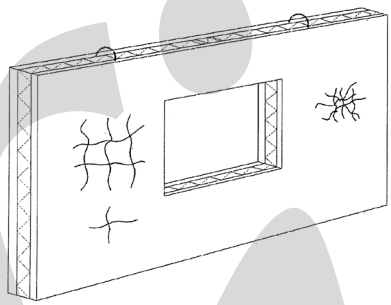
1: Cracking at panel sides



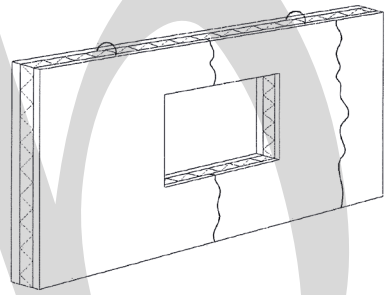
2. Cracking at openings, corners or at lifting devices



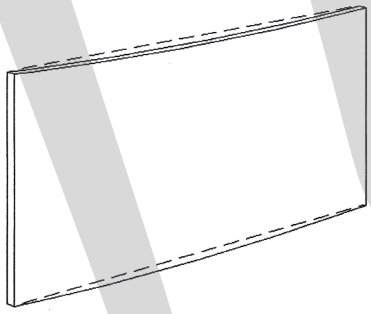
3: Surface cracking



4: Flexural cracks



5: Bowing and other dimensional tolerances



6: Surface failure and dirty surfaces

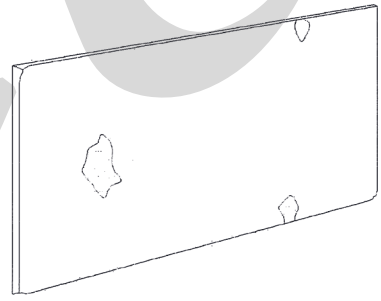


Fig. 7-6 Imperfections of the outer layer of sandwich panels or cladding panels (adapted from *fib* Bulletin 41).

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7.5 Cleaning

7.5.1 Protection

Precast insulated sandwich panels should be delivered to the jobsite in a clean and acceptable condition. Upon arrival, the erector should recoat all welds and abraded steel with a rust inhibitor or, in case of galvanised plates, with a cold galvanising coating. The erector is normally responsible for the repair of any chipping, spalling, cracking and other damage to the sandwich panels after delivery to the jobsite. The general contractor assumes responsibility for panel protection and any subsequent repair after panel erection.

Any mortar, grout, plaster, stains, or other secondary material marks on the panels during the course of general construction should immediately be washed off with clean water, or cleaned as otherwise required. Care should be taken as rainwater or water from the construction site can wash across building materials and cause discoloration of exposed panels.

Arrangements should be made by the general contractor to provide protection for adjacent materials (such as glass and aluminium) that may be damaged by welding. Otherwise, the adjacent materials should not be installed until the panels are in place, fixed, repaired, and cleaned.

Should cleaning be required, exposed panel faces may be washed with a cleansing agent mixed with hot water and a good fibre brush if required. Panels should be thoroughly rinsed with clean clear water after washing. Cleaning solutions must never be allowed to dry on the concrete surface that will be exposed to view. The final finish should be sound and have exposed concrete free of all laitance, dirt, stains, smears, or other blemishes.

7.5.2 Stubborn stains

If stains remain after cleaning with a stiff fibre brush and cleansing agent, the surface of the panel should be thoroughly wetted with clean clear water and then scrubbed with a dilute solution of muriatic or hydrochloric acid. The concentration of this solution may be increased to a maximum of 5 percent muriatic or hydrochloric acid, but weaker solutions should be tried first. A thorough washing with clean clear water should immediately follow the application of the acid solution.

Acid cleaning must not be done on honed and polished surfaces or if there are soluble aggregates such as limestone or marble within the panel. Acid cleaning may also change the appearance of sandblasted surfaces. When applying the acid solution, care must be taken to

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prevent damage to any adjacent materials that may be susceptible to acidic damage. Glass and aluminium are especially susceptible during the application of the acid solution.

Repeated applications of a cleaning acid solution on the visible surface of the panels may change the colour and/or texture of the surface. The effect on appearance may necessitate extensive washing of an entire wall or even all exposed panels on a project.

Other commercial cleaning agents may be desirable in lieu of acid. Because muriatic (diluted hydrochloric) acid may leave a yellow stain on white concrete, a 3 to 5 percent phosphoric acid solution may be preferable on white or very light concrete panels.

7.5.3 Sandblasting and steam cleaning

High pressure sandblasting and steam cleaning are also common methods to clean panels. An experienced operator should be used for sandblasting of panels. Sandblasting may dull the aggregate or change the colour and/or texture so that it no longer matches the remainder of the structure.

A small area, preferably on a mock-up panel, should be trailed and approved before proceeding with the work.

7.5.4 Sealers

If panels that have been sealed before transport to the site require cleaning, it may be necessary to remove the sealer and recoat the panel after cleaning.

Surface sealers should never be applied or reapplied until all repairs and cleaning have been completed.

7.6 Patching and Repair

7.6.1 General

A certain amount of repair is routinely expected on all architectural panels.

Minor chipping of sandwich panels during transportation, handling and installation at the jobsite can be expected. Minor damage to panels can be repaired after erection, but major spalls or cracks may require an engineering evaluation (see table 7.5).

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Repair work requires expert craftsmanship if the end result is to be both structurally sound and pleasing in appearance. Careful planning is required to determine whether the repairs can economically match the existing surface concrete both in colour and texture, and be structurally sound. In some cases, it may be more feasible to recast the panel. All patching and repairs should be fully cured, cleaned, and dry before installation of sealant in the joints between panels.

General guidelines for repair of concrete are found in literature around the world, such as ACI 562. The repairs should conform to the contract documents, project specifications and be architecturally satisfactory.

7.6.2 Repair considerations

Each panel produced should be evaluated as part of the quality control process to determine if any imperfections in the concrete require repair. Many repairs can accentuate the flaws within the panel, rather than remove them. Slight colour variations can be expected. Should minor surface blemishes be observed, attempt hand tooling, or rubbing before undertaking any patch repairs. Needle scaling, bush-hammering, or other mechanical tooling can also be effective in blending in offsets or variations in colour and texture.

Use a jobsite mock-up or a damaged or rejected panel to develop a patch mix design and practice repair and texture techniques. In most cases, it is better to complete the preparation of all finishes on the sandwich panels before beginning any patching or repairs. Recent repair areas can be damaged if repairs are made ahead of the panel finishing.

Repairs such as epoxy-filled crack repairs should be done before sandblasting or other high pressure finishing. Blasting before the epoxy work will cause the crack to have rounded edges, and it will be more difficult to minimise the crack appearance.

Upon completion of all repairs, all patches and repair will need to be cured. These areas will require better curing and greater weather protection than the original concrete. The correct tools, staging or scaffolds, and safety or protection equipment should be set for all finishing personnel.

7.6.3 Chips and spalls

Chips, spalls, and areas of unsound concrete may be removed with a hand-held or pneumatic chisel. The repair area should be chipped out to a depth of at least 1.5 times the maximum size of aggregate to assist in physically holding the patch mix into the concrete matrix. All dust must be brushed or blown from area to be repaired prior to commencing the repair.

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The entire area to be repaired, as well as adjacent surfaces, should be pre-wetted before applying a recommended bonding agent. A stiff pre-designed patch mix should be applied onto the repair area and compacted for maximum density by dry tamping.

Large repair areas will need coarse aggregate in the patch mix or the aggregate must be hand placed and rodded into the patching grout. Strike the repair area level and add any surface texturing while the concrete is still plastic. Curing should commence immediately. If the spalled-out piece of concrete is available and fracture surfaces still mate, the easiest repair may be to adhere the spalled concrete back into place using an epoxy adhesive. The fractured surface of the panel and spalled piece should both be painted with the epoxy adhesive. Apply enough epoxy so that some epoxy will squeeze out when the mated pieces are clamped together. An epoxy with sufficient viscosity to prevent sagging or running on vertical surfaces should be used for this type of repair.

It may be necessary to drill through the spalled piece and into the panel to set pins or reinforcing bars to increase anchorage of the repair.

7.6.4 Crack repair

Panels may crack during transportation and erection. Structural and visual acceptability of cracks should be determined by the engineer, architect and owner. The repair method for a crack will depend on its size, location, and the structural reason for the crack occurring. Cracks that are non-structural or have no significant structural implications may be chipped or routed out and repaired in the same way as chips and spalls (Section 7.6.3).

Cracks that are relatively short but require structural repair may be chipped or routed out to a minimum depth of 1.5 times the maximum aggregate size and filled with a non-sagging epoxy adhesive or stiff mortar. When the crack is on the exposed finish face of the panel, the epoxy repair preparation may be taken deeper into the panel to allow for application of a surface patch mix or fairing coat to match adjacent surfaces.

Longer or deeper crack repairs may require epoxy injection using a low viscosity, 100 percent solid materials. The epoxy colour (amber, grey, white or pigmented) should closely match the exposed concrete surface. This approach can be used on all cracks wider than about 0.05 mm. Epoxy injection depends on the temperature of the concrete and the viscosity of the epoxy. See epoxy manufacturer's specification and installation procedures to ensure proper application and usage. The typical epoxy repair procedure is to:

- Clean the cracked area thoroughly.
- Drill holes for entry ports along the crack, half the thickness of the panel depth and space entry ports along crack at intervals approximately equal to the thickness of the panel.

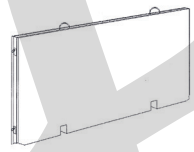
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- Provide a temporary surface seal with either wax, grout, hydraulic cement or an epoxy resin sealant.
- Inject low viscosity, 100 percent solids, epoxy into injection ports beginning with the bottom or lowest port. An injection pressure of approximately 90 psi is usually recommended.
- Continue to inject from the lowest port until epoxy flows from the next highest port along the crack.
- Plug each injector port after it has been filled and continue injecting from the higher port.

Continue the procedure until the entire crack has been filled. After the epoxy has cured, remove the temporary surface seals, ports, and any extra epoxy. Surface texturising or sandblasting of the repaired concrete area may be necessary to remove all traces of epoxy on the surface seal coat.

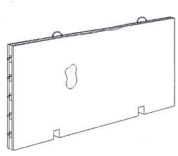
Table 7-5 Imperfections of Loadbearing Walls and Sandwich Panels (adapted from *fib* Bulletin 41).

Case 1: Missing dowel bars or broken corners

	Cause	Prevention	Effect	Repair
	**Improper production:**			
	a. Missing dowel bars or connectors (failure of manufacture)	• Better quality assurance	• Limitations in structural performance. • Lack of connectors can prohibit the assembly	• Check structural capability • Install new dowel bars or new welded connectors • If repair not possible, the unit may be rejected
	b. Broken corners (failure at demoulding, storage or during transportation)	• More careful handling	• Aesthetic error • In some cases, may need modification of support surfaces	• Filling with grout or screeding

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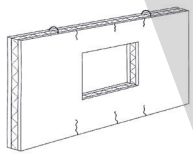
Case 2: Uneven support or failures at concrete surfaces



Cause	Prevention	Effect	Repair
Improper production:			
a. Uneven support surfaces or poor finishing of the surface	• Better finishing and quality assurance	• Risk of failure at assembly	• Levelling of support surfaces with concrete of the same strength, possibly before assembly of upper structure
b. Failure of concrete surfaces (see before)	• Change of concrete mix and/or vibration technique • Clean and even mould surface	• Typically no structural effect, some additional cost in aesthetic repair	• Plaster or screeding layer before painting

Table 7-6. Imperfections of the outer layer of Sandwich Panels or Cladding Panels (adapted from *fib* Bulletin 41).

Case 1: Cracking at Panel Sides

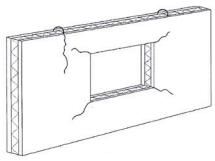


Cause	Prevention	Effect	Repair
Improper production:			
• Plastic shrinkage • Lack of edge reinforcement	• Better curing • Edge reinforcement in outer layer • Less shrinkage in concrete	• Aesthetic inconvenience, if crack width less than 0.1-0.2mm • Steel corrosion, if crack widths wider	• Larger cracks can be injected with grout or epoxy • Surface treatment can be changed to painting or plaster

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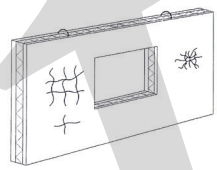
Table 7-6 Imperfections of the outer layer of Sandwich Panels or Cladding Panels (Cont.)

Case 2: Cracking at Openings, Corners or at Lifting Devices



Cause	Prevention	Effect	Repair
Improper production:			
• Cracks at Openings • Plastic shrinkage, concrete dries too fast • Lack of reinforcement	• Better curing • Additional reinforcement • Less shrinkage in concrete	• Aesthetic inconvenience, if crack width less than 0.1-0.2 mm • Steel corrosion, if crack widths wider • Concrete can break during lifting for wider cracks	• Larger cracks can be injected with grout or epoxy • Surface treatment can be changed to painting or plaster • Careful handling and erection may be possible, otherwise the unit may be rejected
• Improper handling Cracks at Lifting Devices • Concrete too fresh during handling of the unit • Incorrect lifting device • Concrete layer too thin	• Concrete strength over 60% of design strength at demoulding • Tilting table moulds • Strengthening of outer layer at lifting point		

Case 3: Surface Cracking

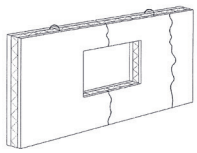


Cause	Prevention	Effect	Repair
Improper production:			
a. Systematic cross-ruled cracks • Separated concrete mix • Plastic shrinkage, concrete dries too fast • Aggregate too small • Insufficient cover to reinforcement (too small)	• Better casting and curing • Larger aggregate size • Check cover to reinforce-ment	• Aesthetic inconven-ience, if crack width less than 0.1-0.2 mm • Steel corrosion, if crack widths wider	• Normally does not influence panel strength, other than durability and frost resistance. • Larger cracks can be injected with grout or epoxy • Surface treatment can be changed to painting or plaster
b. Non-Systematic netcracking • Too much cement paste • Separated concrete mix • Trowelling process failure • Too high temperature gradient	• Check concrete mix proportions • More exact trowel timing • Better curing		

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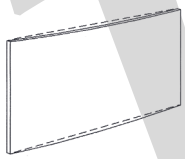
Table 7-6 Imperfections of the outer layer of Sandwich Panels or Cladding Panels (Cont.)

Case 4: Structural Cracks



Cause	Prevention	Effect	Repair
Improper production:			
a. Early cracks (occurs within first week) • Curing of concrete too fast • Shrinkage of concrete restricted (particularly for long panels –moulds for openings, steel connectors, etc.) • Demoulding too early • Insufficient cover to reinforcement (too small)	• Less heat curing and outer layer temperature less than 45°C • Check the mould and tie bars • Concrete strength over 60% of design strength at demoulding • More flexible connectors between wall panels and the skeleton	• Aesthetic inconvenience, if crack width less than 0.1-0.2mm • Steel corrosion, if crack widths wider • Whole panel can be broken at lifting if cracks are protruding	• If cracks are protruding through they should be injected with grout or epoxy • Surface treatment can be changed to painting or plaster • Careful handling and erection may be possible, otherwise the unit may be rejected
b. Occurs at an age over one week • Thermal deformations in the whole skeleton. This may occur during the first year (eg. Ground or Roof level)			

Case 5: Bowing and other dimensional tolerances

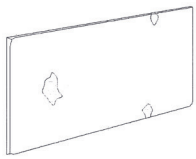


Cause	Prevention	Effect	Repair
Improper production:			
a. Bowing • Variations of density and shrinkage of panel layers • Sun's heat applied to one side only in stockyard and associated creep • Long storage time • Panels too long	• Avoid long storage times and sun exposure for dark surfaces and/or long panels • Careful mixing, vibration and curing	• Aesthetic, influence on the visual appearance both individually and when all panels are viewed together	• Very often panels can be 'pulled' straight with normal or additional connectors
b. Other dimensional tolerances • Insufficient production measures and quality control • Long-term deformations not taken into account during design	• Good measuring systems and quality control	• Can limit architectural or structural performance • Can make the erection work more difficult (or impossible)	• Panels exceeding allowed tolerances may still be acceptable, provided the total erected assembly can be modified to meet the structural and architectural requirements

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Table 7.6. Imperfections of the outer layer of Sandwich Panels or Cladding Panels (Cont.)

Case 6: Surface failure and Dirty Surfaces

	Cause	Prevention	Effect	Repair
	**Improper production:** **a**. Separation of aggregate **b**. Variations in colour or shade **c**. Lime and/or efflorescence at surfaces			• Surface repair or rejection • Small variations accepted. For larger variations, the panel may have to be rejected. • Washing with saltphosphor or acetic acid and water
	• Dirty surfaces (oil, rust, etc.)	• Careful production, storage and transportation		• Surface cleaning or other washing

7.7 Joint Sealing (Caulking)

7.7.1 Joint preparation

Before application of a sealant, concrete surfaces should be sound, smooth, clean and free of all mortar, dust, or other contaminants such as form release agents that may affect adhesion. Some sealant materials cannot be applied to wet surfaces and no sealants should be applied to a frozen surface. Use of a stiff wire brush, light grinding or sandblasting followed by air blowing may be necessary to remove all surface contaminants.

After the joint area has been cleaned, the joint should be wiped with a cloth dampened with an oil-free solvent, or as recommended by the sealant manufacturer. To ensure good adhesion between the sealant and the panel concrete surface, some manufacturers recommend a primer. The sealant and primer combination should be as recommended by the manufacturer. Some primers leave an amber stain if brushed along the exposed panel face. This stain often requires removal by mechanical means and can be expensive. Sealers or sealants should not be applied directly over silicone or acrylic waterproof materials.

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7.7.2 Sealant installation

Sealant application should be carried out when the external temperature is comprised between 5 and 30°C. This installation temperature may vary depending upon the sealant material, humidity, and protection available at the work area.

In cold weather, the joint and the sealant may be heated depending on the manufacturer's recommendations. The installation of sealant can be carried out even in temperatures of -5 to -10°C in dry weather conditions.

It is desirable to use the minimum amount of sealant to make a satisfactory joint. A relatively thin bead is less likely to fail than a thick bead because the thin bead can deform more uniformly. For joints up to 12 mm wide, the depth of the sealant should approximately equal the width. For wider joints, the depth should equal approximately half the width, but typically not more than 12 mm.

The recommendations of the manufacturer should always be followed regarding mixing, surface preparation, priming, pot life and correct installation procedure. Good workmanship by qualified and experienced sealant applicators is important to achieve satisfactory performance.

To ensure quality control many sealant subcontractors may prefer to mix all two-part sealants, load into cartridges, and then flash freeze the cartridges before delivery to the jobsite. If done properly, this will eliminate dust, dirt or moisture contamination. The sealant (caulking) gun should have a nozzle that is the correct size and should provide sufficient pressure to completely fill the joint. Joint filling should be done carefully and completely, thoroughly working the sealant into the joint. The sealant should be smoothed and neatly tooled to eliminate any air pockets or voids.

Backup fillers, or backing rod, used in joints to control the depth of sealant should be installed in the joint with a minimum compression of 30 percent.

The sealant joints described above are called one-stage joints. Several typical situations are shown in Figures 7-7, 7-8 and 7-9.

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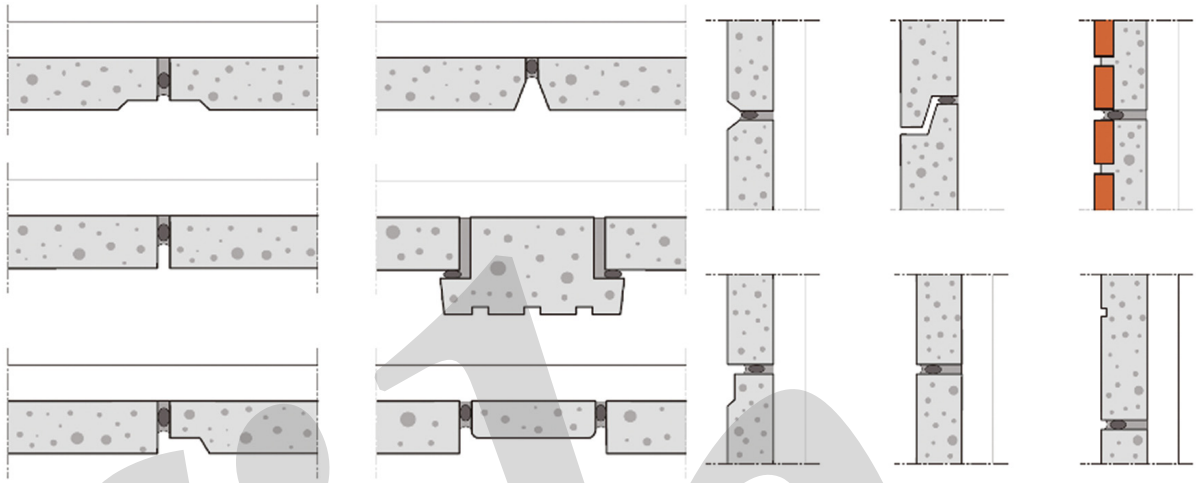


Fig. 7-7 Vertical and horizontal elastic joints of cladding panels

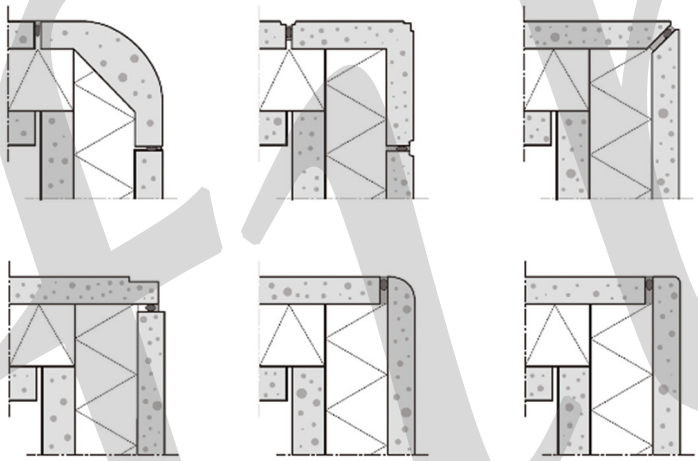


Fig. 7-8 Elastic joints in the corner of sandwich panels

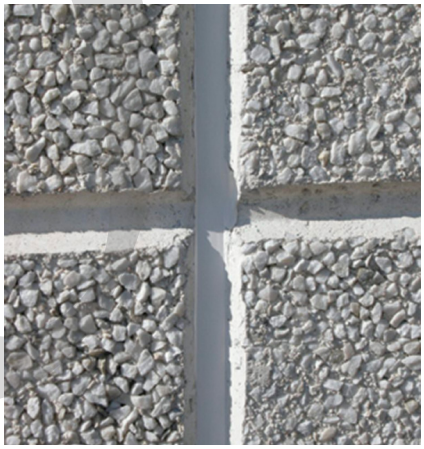


Fig. 7-9 Vertical elastic joint.

7.7.3 Two-stage joints

When a two-stage joint is used, correctly detailed and installed venting and draining are necessary. All horizontal joints should have vent tubes. These are generally located at the junction of the horizontal and vertical joints. Venting of the joint prevents water (either from penetration or from condensation) from collecting between the wall structure and facing panels or within the panel joints, if both the exterior and interior faces of the panels are sealed.

Vent tubes should be 8-12 mm internal diameter polyvinyl chloride or other non-staining materials (see Figure 7-10). The vent tube should slope down to the exterior face of the panel and must penetrate the joint backup filler, or backing rod, so that it allows for free movement

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of air between the outside environment and the cavity. A minimum of two vent tubes per panel or spacing at 1.8-3.0 m centres should be used. Vents should project at least 6 mm (1/4 in.) beyond the sealant exterior face.

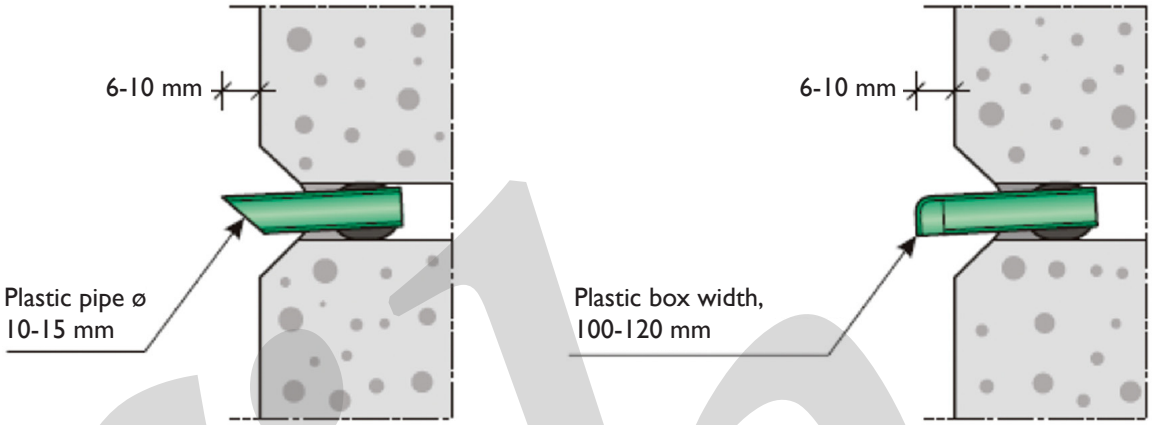


Fig. 7-10 Typical elastic panel joint with ventilation pipes or boxes

When installing a two-stage joint, apply the interior air seal or sealant first. This will minimise the escape of warm moist air from the interior to the joint cavity, thereby reducing condensation.

When installing a fire resistant joint system, if required, the fire-resisting blanket should be installed under a minimum of 10 to 15 percent compression.

7.8 Repair during life-cycle

External concrete sandwich panels and other cladding panels are very durable and they normally have a service life that can well exceed 50 years. The concrete itself may need only cleaning by high pressure washing, however, façade surfaces on the ground floor or street level, may be treated with anti-graffiti coatings or membranes.

Elastic joints between panels need to be renewed typically between 20-25 years. Joint material should be tested for the relevant climate conditions. In hot climates, they must resist high external temperatures and in cold climates low or even freezing temperatures. The joint or sealant material must be able to provide sufficient elasticity as to resist both temperature variations and long-term deformations of concrete.

One possibility to minimise long term maintenance is to hide sandwich panel joints. There are many possibilities in the structural detailing of panels to partially or even completely hide panel joints (see Figure 7-11). In advanced architectural design elastic joints can also be hidden within the façade into things such as window lines, façade corners etc. (see Figure 7-12).

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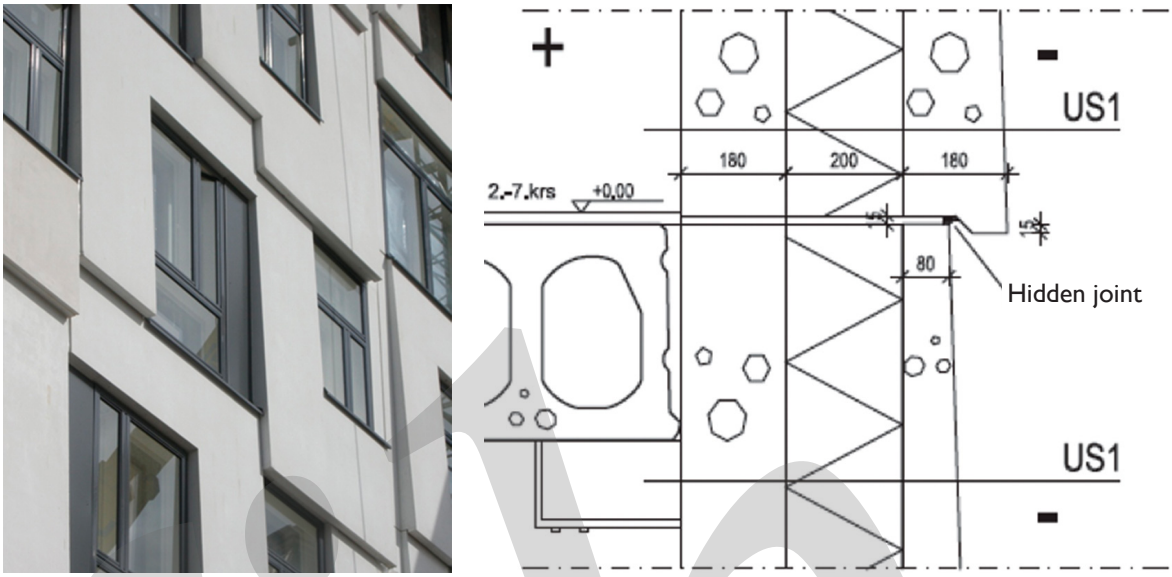


Fig. 7-11 An example showing how panel joints may be hidden

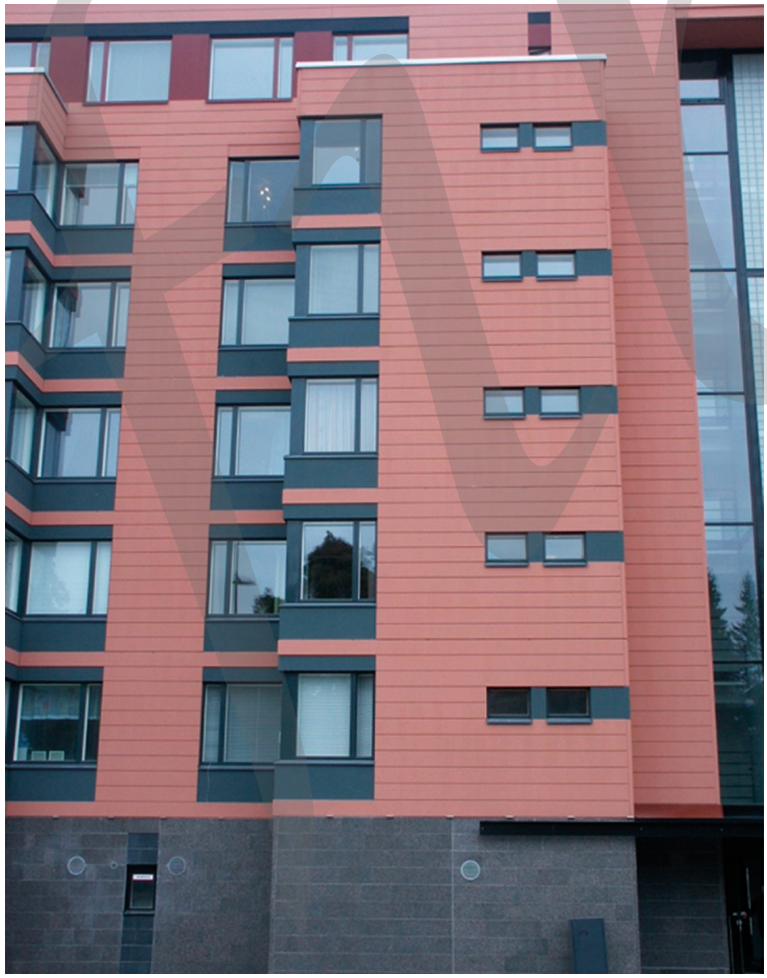


Fig. 7-12 Elastic sealants hidden in the façade

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Appendix A: Typical connections and details

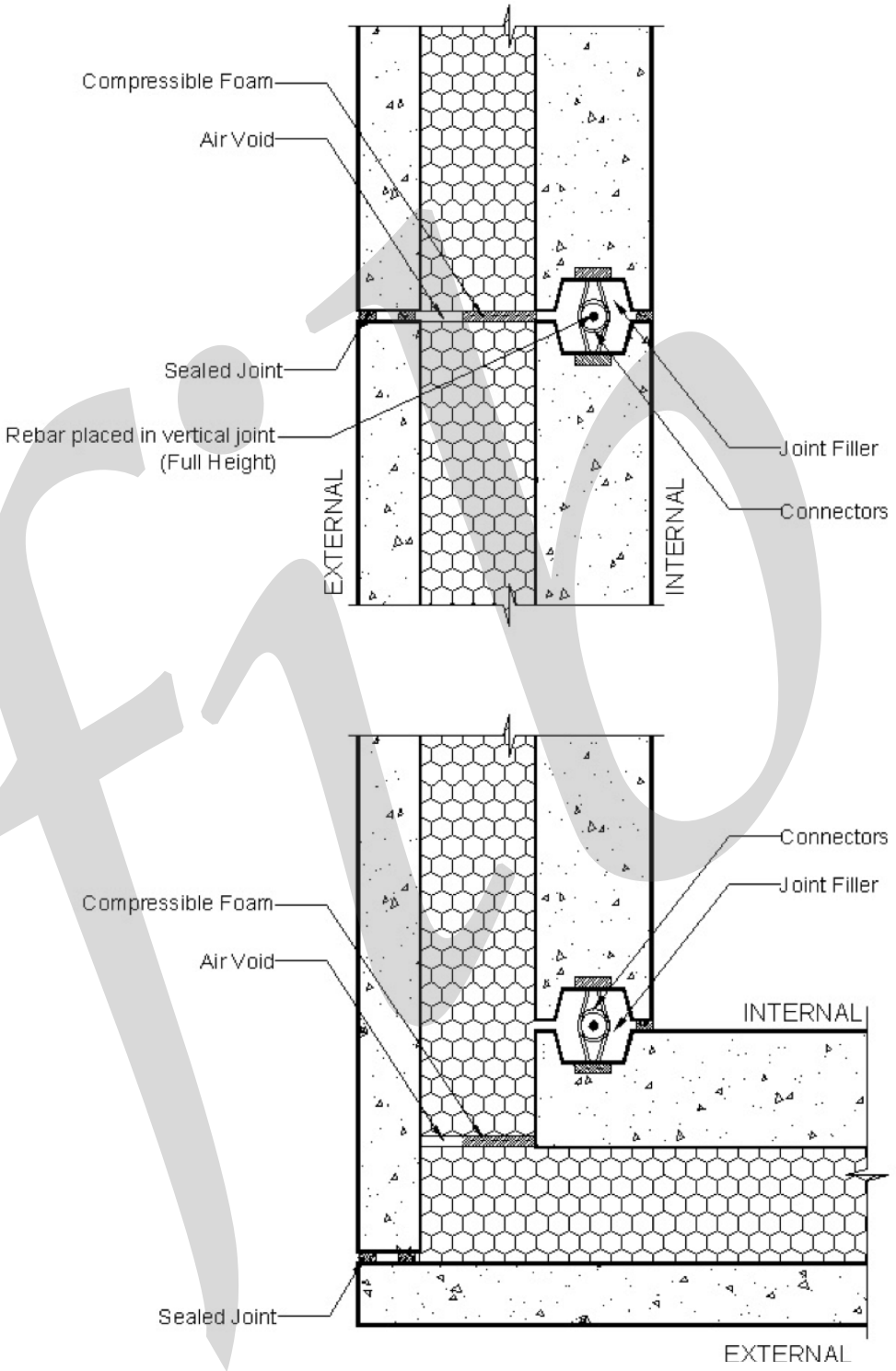


Fig. A-1 Typical Sections Through Vertical Joints

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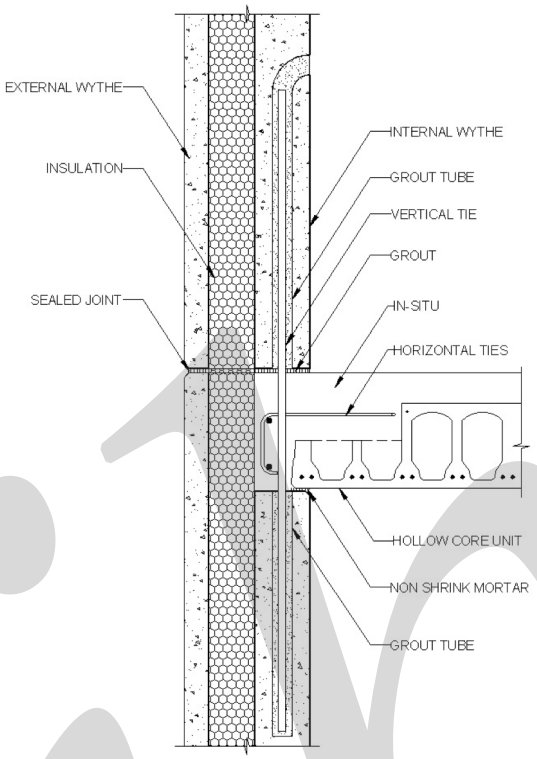


Fig. A-2 Typical Section at Non Load Bearing Slab Edge

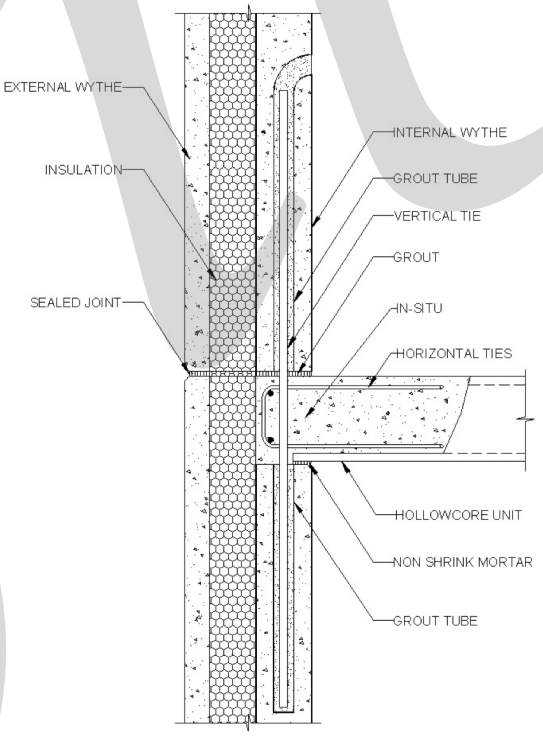


Fig. A-3 Typical Section at Load Bearing Slab Edge

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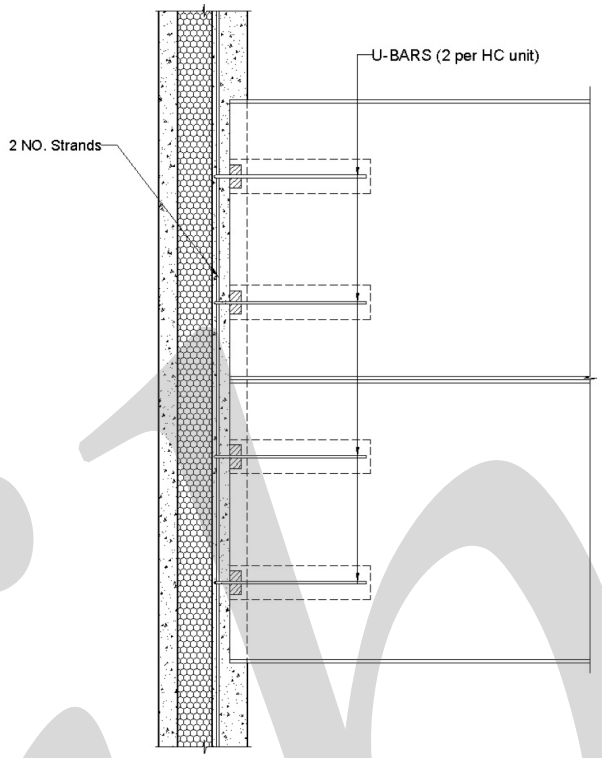


Fig. A-4 Plan Showing Horizontal Tie Connection into Hollowcore Slabs

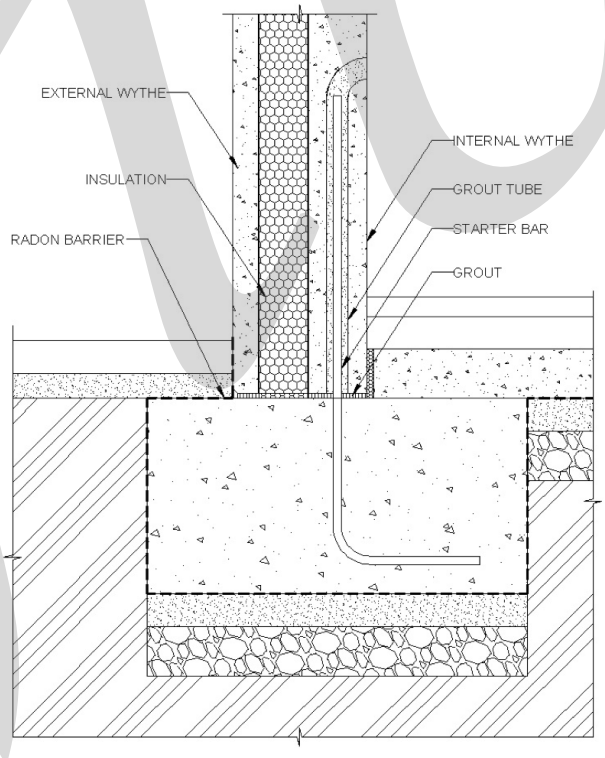


Fig. A-5 Typical Base Section with Starter Bars

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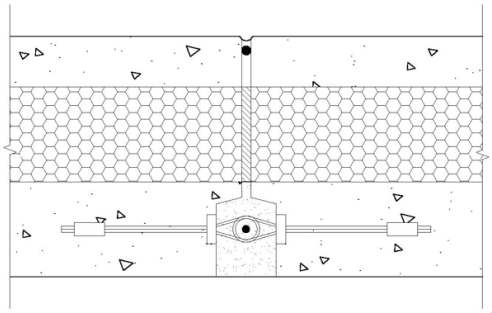


Fig. A-6 Typical Panel to Panel Connection

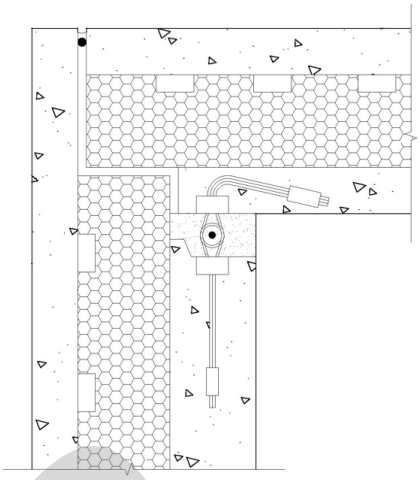


Fig. A-7 Typical Panel to Panel Connection

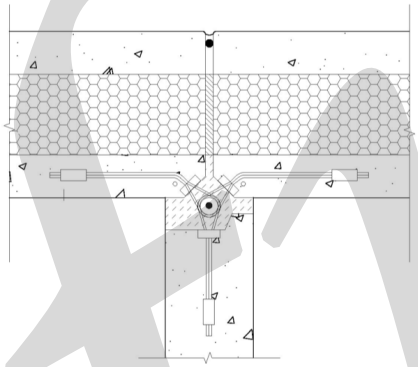


Fig. A-8 Typical Panel to Panel Connection

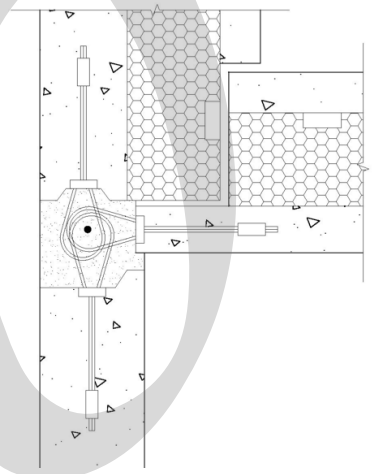


Fig. A-9 Typical Panel to Panel Connection

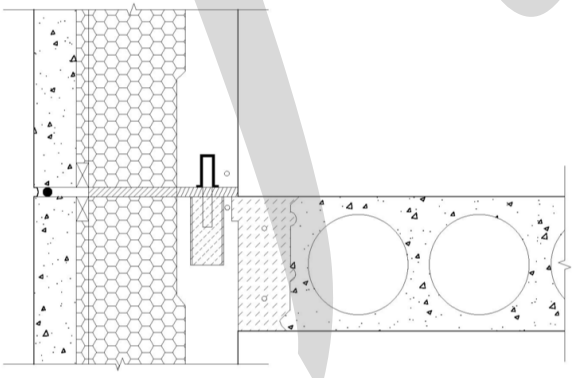


Fig. A-10 Typical Panel to Floor Connection

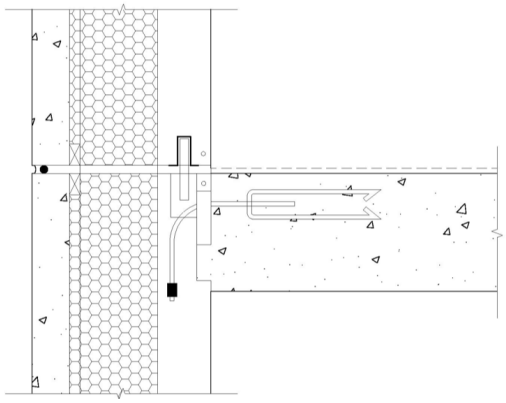


Fig. A-11 Typical Panel to Floor Connection

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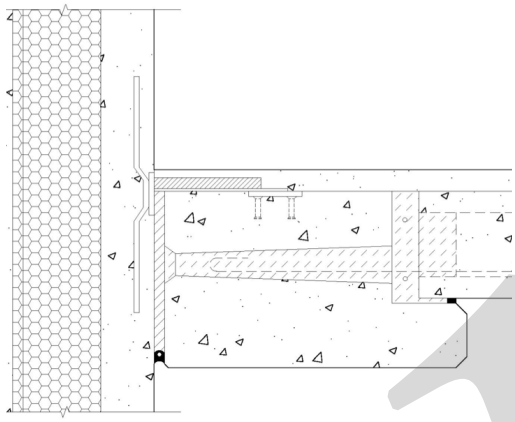


Fig. A-12 Typical Panel to Floor Connection

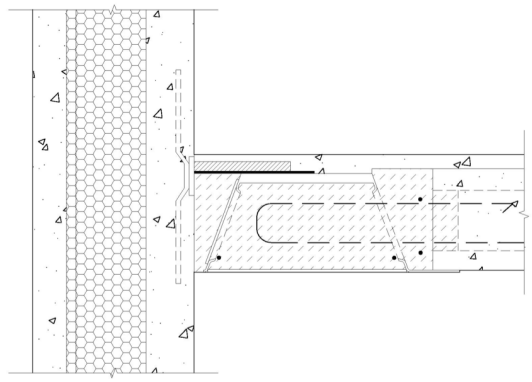


Fig. A-13 Typical Panel to Structure Connection

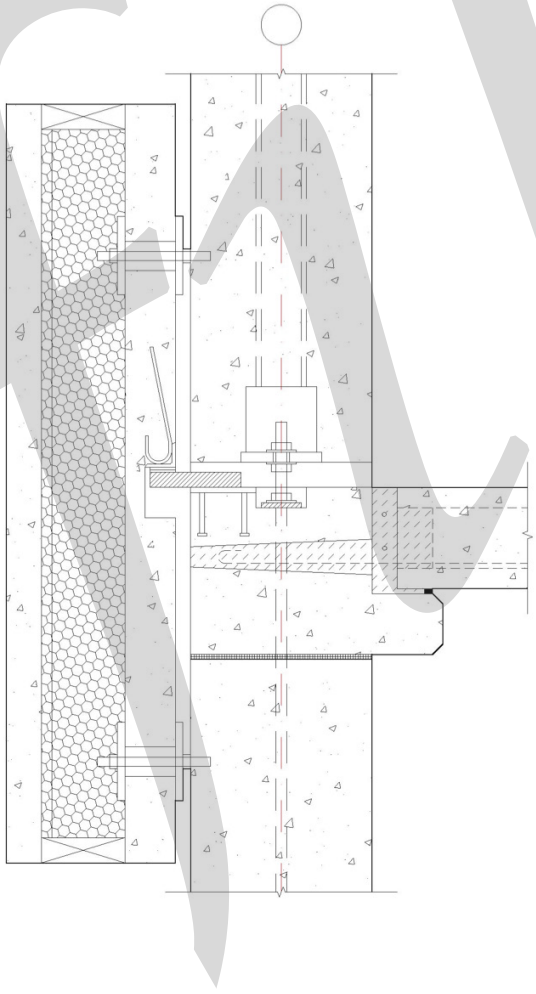


Fig. A-14 Typical Panel to Structure Connection

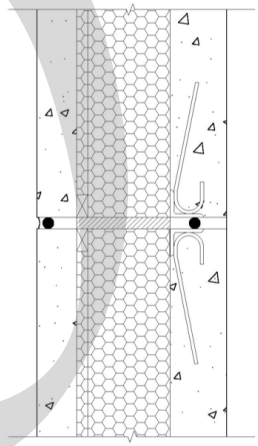


Fig. A-15 Typical Vertical Panel to Panel Connection

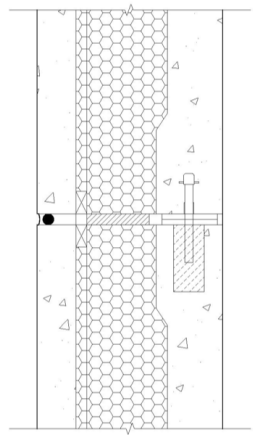


Fig. A-16 Typical Vertical Panel to Panel Connection

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Appendix B: Design of connector/tie loads due to temperature differences in the outer wythe (non-composite precast insulated sandwich panels)

B.1 Introduction

Dr. Ing. Günther Utescher's article1* in Die Bautechnik (5/1973) is still considered state-of-the-art in Germany and many other European countries when it comes to the temperature design of three- or four-layer sandwich panels.

According to Utescher, the temperature difference between the inside and the outside surface of the outer wythe causes a warping of the outer layer that can be defined as a constant bending moment mT longitudinal to the edges of the outer wythe.

$$m_T = \frac{E_c \ \alpha_T}{12} \ \Delta T \ t^2$$

Where:

E_c = Modulus of Elasticity of Concrete
α_T = thermal coefficient of concrete
ΔT = temperature gradient2**
t = thickness of the outer wythe

The warping of the outer layer is restrained by anchors and ties. For rectangular sandwich panels with a nearly rectangular tie grid and a grid ratio between 0.5 and 2.0, anchor/tie loads can be designed with an approximation method based on the continuous beam theory: in both panel directions, the outer wythe is divided to beam strips with anchors/ties acting as supports.

---

* *Der Tragsicherheitsnachweis für dreischichtige Außenwandplatten (Sandwichplatten) aus Stahlbeton*
** German approach: Δ T = 5 K for 3-layer sandwich panel / 1.5 K * t [cm] for 4-layer PISP

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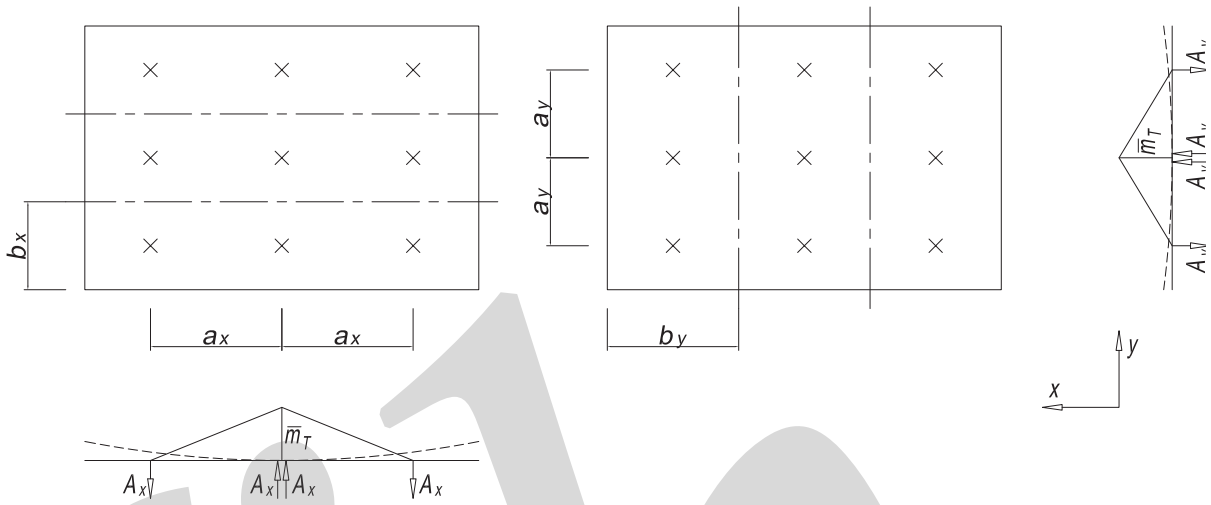


Fig. B-1 Partition of the panel into beam strips

The restraint loads A can then be calculated for each direction as:

$$A = \bar{m}_T \frac{b}{a}$$

with:

$$\bar{m}_T = 1.5\ m_T$$

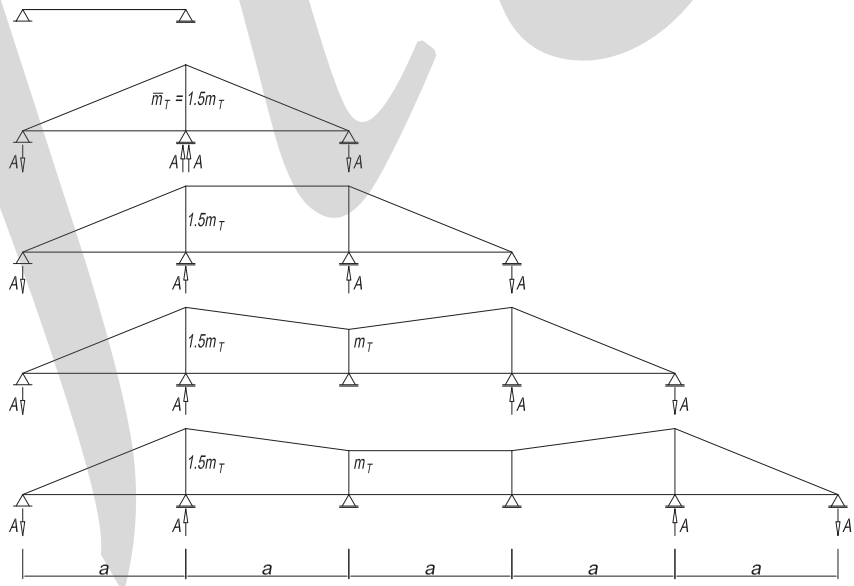


Fig. B-2 restraint loads for different span numbers

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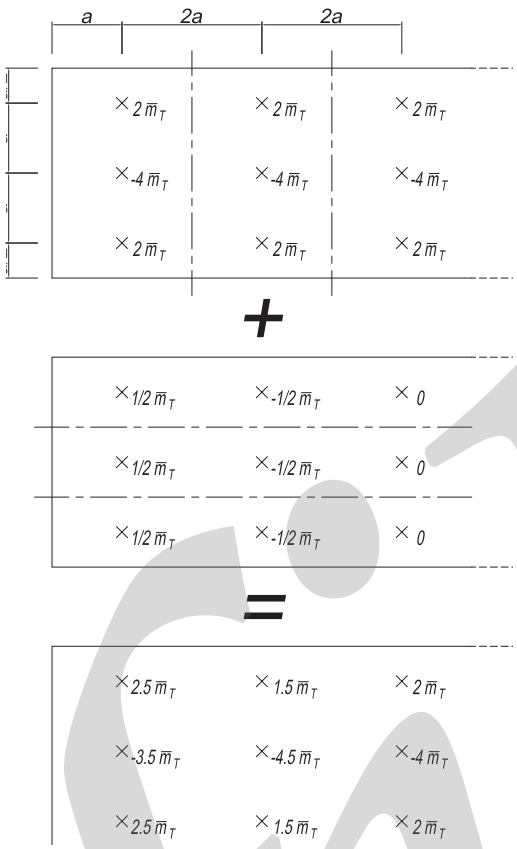


Fig. B-3 Example for the superposition of restraint forces for a grid ratio = 0.5

When calculating the decisive anchor-/tie-load, the temperature restraint forces are supplementarily to be superposed with adverse wind loads.

Design of anchors/ties due to temperature differences between the inner and the outer wythe (non-composite sandwich panels)

Due to the position of the insulation layer, the outer wythe is more exposed to temperature changes – e.g. between day and night – and therefore will expand or contract more than the inner wythe. For non-composite sandwich panels, this is simple since the outer and the inner wythe can perform independently. However, when choosing ties and anchors to connect the two layers, it is important to make sure that the anchors/ties have been tested regarding their fatigue strength. The German approach is to limit the stress caused by the displacement to a value that has been proven to have no effect on the load bearing capacity of the anchors/ties in the long term.

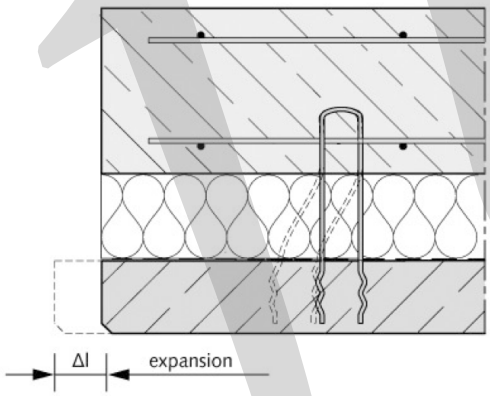


Fig. B-4 Displacement of tie due to wythe expansion

Since the relative displacement between the two concrete layers – and therefore the bending stress in the anchors/ties – correlates with the distance from the centre/fix point, stress in the anchors/ties is usually limited by allowing only certain maximum distances between centre/fix point and anchors/ties.

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B.2 Example of a Non-Composite, Cladding Precast Insulated Sandwich Wall Panel Design According to Eurocode

B.2.1 General considerations

The building geometry of this example, as well as the data related to its seismic response, were adapted from the example presented in the work examples book of EC 8 [1].

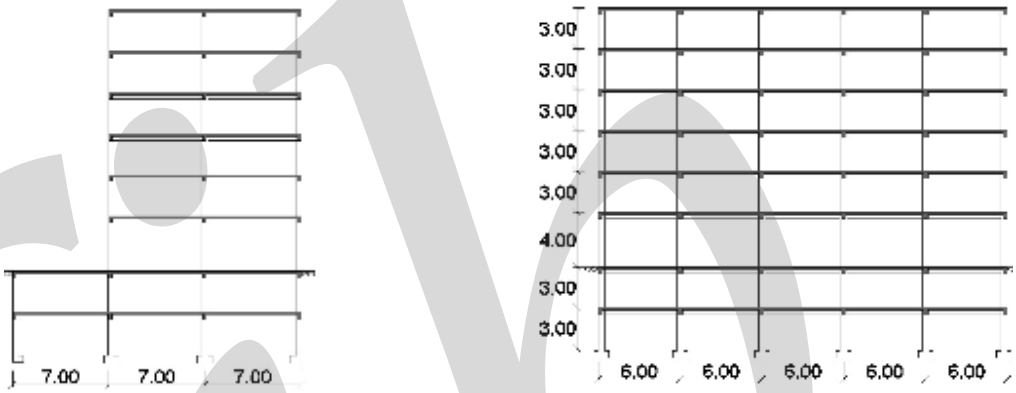


Fig. B-5 – Building schematic cross-sections

B.2.2 Panel geometry

The panel example should be applied in the XX direction façade for the 2nd and upper floors. The panel geometry is presented in Figure B-6 and Table B-1. The corbel geometry is schematically presented in Figures B-7 and B-8. The dimensions of the two corbels are: Hc=0.15 m, Lc=0.50 m, tc=0.20 m and H'c=0.05 m. The cross-section of the panel is showed in Figure B-8 and the thickness of the layers are presented in Table B-1.

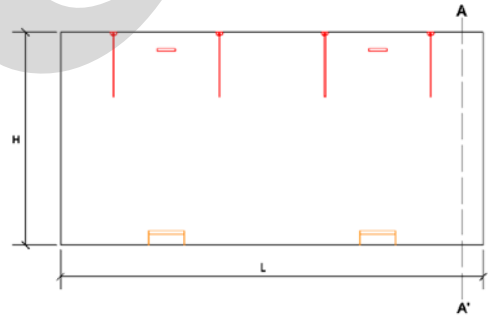


Fig. B-6 Front view of the panel

Table B-1 Panel Geometry

Layer	H (m)	L (m)	t (m)
Inner layer	3.00	6.00	0.12
Insulation	3.00	6.00	0.10
Exterior layer	3.00	6.00	0.07

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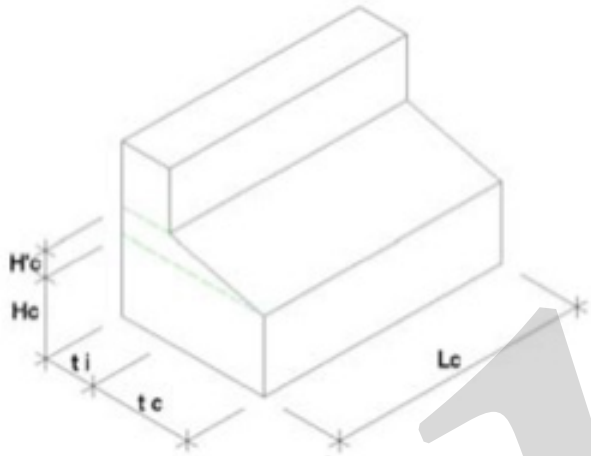


Fig. B-7 Corbel geometry

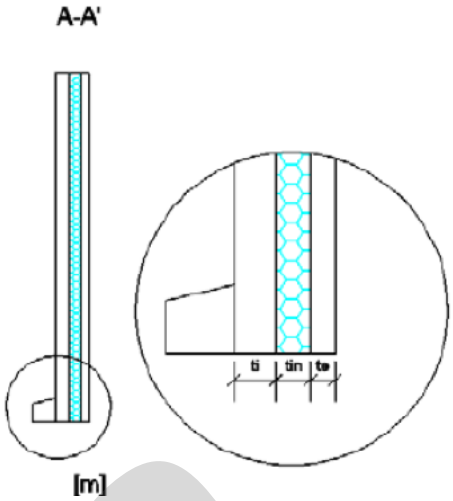


Fig. B-8 Cross-section of the panel

B.2.3 Materials characteristics

B.2.3.1 Concrete

The concrete class is defined according to EC 2 [2] as C35/45. The characteristic compressive cylinder strength of concrete at 28 days (f_{ck}) is equal to 35 MPa and the design value of the concrete compressive strength is calculated as $f_{cd}=f_{ck}/1.5=23.3$ MPa. An elastic modulus (E_{cm}) of 34.1 GPa and a concrete tension strength (fctm) of 3.2 MPa is assumed.

B.2.3.2 Reinforcing steel

The reinforcing steel is assumed to belong to Class B500B. The characteristic yield strength of reinforcement is fyk=500 MPa and the design yield strength of reinforcement is f_{yd}=435 MPa.

B.2.3.3 Load cases

Sandwich wall panels are exposed to various load cases until they are installed in their definitive place. The panels must withstand to the forces due to demould, transport, elevation, service and seismic loads.

B.2.4 Demoulding

The demoulding action provide stresses at early age, when the concrete doesn't have its full strength yet. To guarantee the structural integrity, the concrete strength at that age must be considered.

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With a hydraulic tilt-up casting table, the panels can be rotated to be demoulded. When the table is in vertical position, lifting anchors on the panel are used to demould the panel, taking advantage of a higher moment of inertia.

The lifting anchors have to support the panel weight as well as the adhesion force to the mould and must respect all the supplier requirements.

The total self-weight of the panel is: SW=86.4 kN

When the precast unit is first lifted out of the mould, the required force may be a multiple of the actual concrete weight. This is caused by suction, adhesion and friction between the mould and the concrete unit. Assuming a smooth, oiled mould, the following adhesion force is considered: q= 1 kN/m^2 [3].

Considering A=18 m^2 as the contact area between the concrete and the mould, the adhesion Force is: Ha=q × A=18 kN and the demoulding design Force is:

$$F_{d.Ed}==SW + Ha=104.4 \text{ kN}$$

If the demoulding occurs when the concrete is 2 days old, a compressive strength of 16.9 MPa is achieved. This strength is enough to guarantee a 40.9 kN resistance of axial force on each lifter.

In order to balance the panel, four lifting anchors are adopted considering the HALFEN - DEHA lifting anchor system catalogue [3].

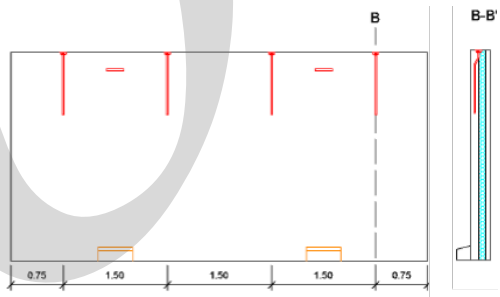


Fig. B-9 Front view of the panel with the lifting anchors

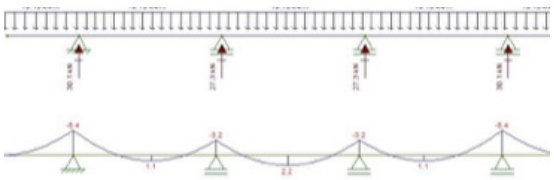
B.2.5 Transport and elevation

Assuming a stationary crane with a lifting speed over 90 m/s, implies an impact factor Ψ =1.4 [3]

$$F_{t.e.Ed} = SW\ \Psi = 120.925 \text{ kN}$$

$$f_{t.e.Ed} = \frac{F_{t.e.Ed}}{L_i} = 120.925 \text{ kN m}^{-1}$$

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The adopted lifting anchors system is strong enough to support the imposed loads at any stage.

Fig. B-10 Loads imposed by the lifting system, corresponding reactions and bending moments

B.2.6 Seismic Load

Seismic load can be replaced by an equivalent static load. The value of the static load is the product of the panel mass by its seismic acceleration. The maximum acceleration of all the floors should be considered. The design value considered for the panel acceleration due to seismic action is:

$$A_E = 2.56 \text{ ms}^{-2}$$

Adopting a Seismic Equivalent Static Load:

$$W_E = A_E \frac{SW}{g} = 22.548 \text{ kN}$$

results in an equivalent pressure of:

$$w_E = \frac{W_E}{L_i \; H_i} = 1.223 \text{ kNm}^{-2}$$

B.2.7 Wind Pressure

A wind pressure of 1.1 kN/m^2 is assumed. This value is plausible for a 19 m height building in some European areas.

$$fw = 1.1 \text{ kNm}^{-2}$$

B.3 Combination of Actions

In the final position, the panel is exposed to its self-weight, the wind, and the seismic load. The structural analysis of the panel is made independently in the vertical and horizontal directions.

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The imposed service loads on the panel are the self-weight and the wind pressure. Thus, the fundamental combination of actions is given by:

$$f_{Ed}=\gamma_G\ G+\gamma_Q\ Q$$

with the safety factor for permanent actions , $\gamma_G=1.35$, and the safety factor for variable actions $\gamma_Q=1.50$.

Seismic actions should be combined with the other variable actions with a reduction factor Ψ. The only variable action to combine with the seismic action is the wind and its Ψ factor is in EN1990 (Table A1.1 of annex A1): Ψ0.w=0.6; Ψ1.w=0.2; Ψ2.w=0.

Thus, the seismic combination of actions is given by:

$$f_{Ed}=G+\Psi_{2.w}\ f_w+A_{Ed}$$

The horizontal design load is the maximum between the fundamental and the seismic combination.

1) Fundamental Combination

$$f_{w.Ed}=\gamma_Q\ f_w=1.65\ kNm^{-2}$$

2) Horizontal design load

$$f_{S.Ed}=\ \Psi_{2.w}\ f_w+w_E=\ 1.22\ kNm^{-2}$$

3) Horizontal design load

$$F_{H.Ed}=\max\ (f_{w.Ed}\ ;\ f_{S.Ed})=1.65\ kNm^{-2}$$

The vertical design load due to weight is:

$$S_{Wed}=\ \gamma_G\ S_W=116.61\ kN$$

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B.4 Structural analysis

A finite element analysis (FEA) was carried out for the structural analysis of the panel. The bending moments in the panel are schematically shown in Figure B-11 . The design moments and reactions obtained from the FEA are presented in Tables B-2 and B-3.

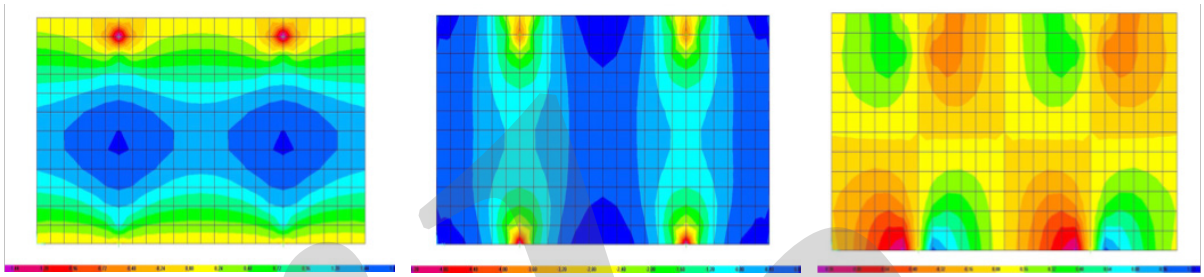


Fig. B-11 Bending moments in the panel

Table B-2 Design Moments obtained from the FEA

M_{Ed}	Max ($kNmm^{-1}$)	Min ($kNmm^{-1}$)
$M_{Ed\,X}$	2.38	- 2.36
$M_{Ed\,Y}$	3.73	- 5.8

Table B-3 Reactions at supports obtained from the FEA

Support	XX (kN)	YY (kN)	ZZ (kN)
Upper	0.00	0.00	8.10
Corbel	0.00	57.71	6.75

B.5 Design

B.5.1 Concrete Cover

Concrete cover values are assumed according to Eurocode 2 [2] restrictions for precast fabrication:

Interior Layer: $c_{nom.i}$=20 mm
Exterior Layer: $c_{nom.e}$=30 mm

B.5.2 Upper Connectors

The design value for the reaction in the upper connectors is 8.1 kN of axial pull in each one.

The HALFEN cast-in channel HZA 29/20 was adopted since it only requires a panel thickness of 100 mm and has a pull resistance of 2x8.5 kN resulting in a Nrd of 17 kN.

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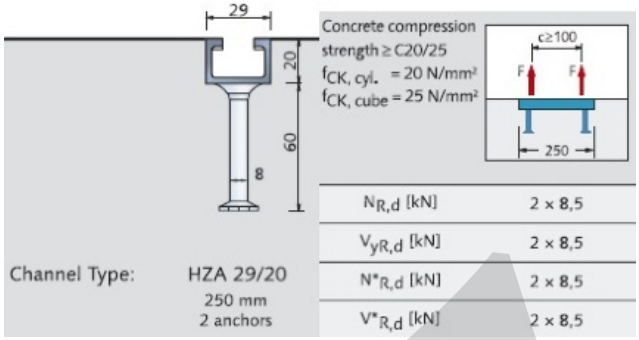


Fig. B-12 Characteristics of HALFEN cast-in channel HZA 29/20 adopted

B.5.3 Wythe Anchors

The anchors can be separated in three different groups: the support anchor, the torsional anchor, and the restrain anchors.

In this panel example the HALFEN connectors were chosen. A cylindrical sleeve connector is adopted for the support anchor combined with a flat plate connector as torsional anchor and pin connectors as retrain ties.

Anchors manufacturers have their own software to allow a correct distribution of the anchors in the panel. Adopting the Halfen connectors with the MVA system and the Halfen SPA software, the following anchor distribution is obtained.

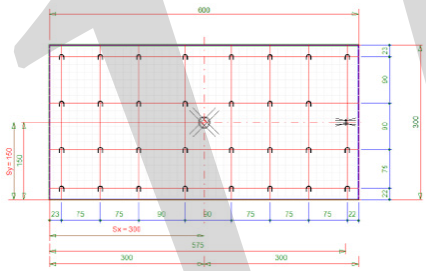


Fig. B-13 Anchor distribution in the panel

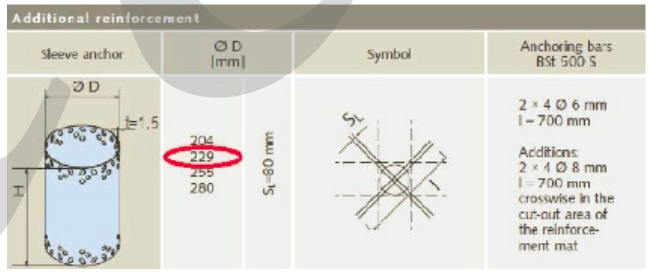


Fig. B-14 Support Anchors: 1 x SP-MVA-225-229

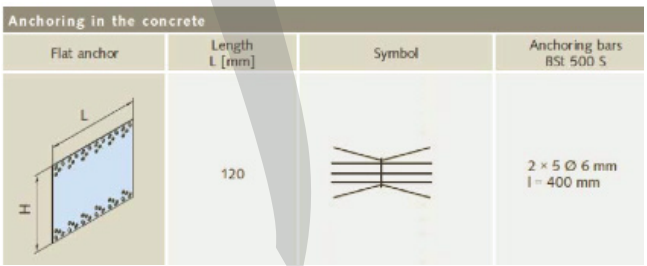


Fig. B-15 Torsional Anchors: 1 x SP-FA-225-120



Fig. B-16 Restrain Pins: 31 x SPA-N-04-220

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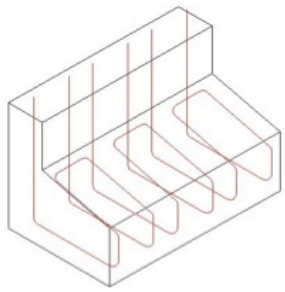


Fig. B-17 Schematic representation of the corbel main reinforcement

B.5.4 Corbel Design

A strut and tie model was used in the design of the corbel. Figure B-17 shows a schematic representation of the corbel reinforcement. The rebar area is:

$A_{s.min}= F_{t.max} / fyd =3.45\ cm^2$ ($6\Phi10 = 4.71\ cm^2$)

With $F_{t.max}$=150 kN based on calculation.

B.5.5 Structural Layer Reinforcement

$d_w = 0.085$ m

$A_{cw}=t_i \ 1\ m = 0.12\ m^2$

$A_{s.v.min}=0.002\ A_{cw} = 2.4\ cm^2$

$w_{w.min} = A_{s.v.min}\ f_{yd} /(f_{cd}\ 1\ m\ d_w) = 0.053$

$\mu_w=w_{w.min}\ (1-0.5\ w_{w.min})= 0.051$

$M_{Rd.as.v.min} = \mu_w\ fcd\ 1\ m\ d_w^2 = 8.64$ kNm

$M_{Ed} = 2.38\ kNmm^{-1}$ ($A_{s.min}$ is enough)

$A_{s.v}=A_{s.v.min} / m= 2.4\ cm^2/m$

(Φ 8 // 20cm [2.51cm^2/m])

$A_{S.v.max} = 0.04\ Acw = 48\ cm^2$

$A_{s.h.min} = min(0.25\ A_{s.v}, 0.001\ A_{cw}\ m^{-1})=$

0.6 cm^2/m (Φ 6 // 30cm [0.94cm^2/m])

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Figure B-18 shows a front view with a schematic distribution of the panel reinforcement.

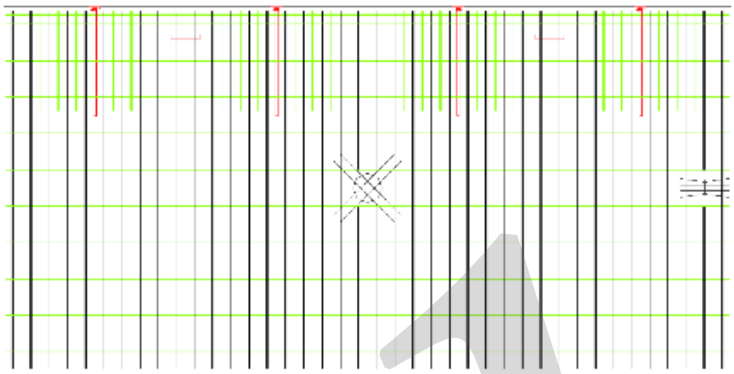


Fig. B-18 Front view of the panel reinforcement

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[1] P. Bisch, E. Carvalho, H. Degee, P. Fajfar, M. Fardis, P. Franchin, M. Kreslin, A. Pecker, P. Pinto, A. Plumier, H. Somja, G. Tsionis (2012). "Eurocode 8: Seismic Design of Buildings Worked examples". European Commission, Joint Research Centre. JRC 68411. doi:10.2788/91658

[2] EN 1992-1-1. Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. CEN.

[3] HALFEN - DEHA lifting anchor system catalogue. Accessible online at web: www.alcor.com.ar

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DBF - Dansk Betonforening, Denmark
SB - Suomen Betoniyhdistys, Finland
AFGC - Association Française de Génie Civil, France
DAfStb - Deutscher Ausschuss für Stahlbeton, Germany
Technical Chamber of Greece
University of Patras, Department of Civil Engineering, Greece
Hungarian Group of the *fib*
The Institution of Engineers, India
fib-Indonesia
Department of Technical Affairs, Iran
IACIE - Israeli Association of Construction and Infrastructure Engineers
AICAP - Associazione Italiana Calcestruzzo, Armato e Precompresso, Italy
CTE - Collegio dei tecnici della industrializzazione edilizia, Italy
ITC - CNR, Istituto per le Tecnologie della Costruzione, Italy
ReLUIS, Italy
JCI - Japan Concrete Institute
JPCI - Japan Prestressed Concrete Institute
LCS - Lebanese Concrete Society
Administration des Ponts et Chaussées, Luxemburg
fib Netherlands
NZCS - New Zealand Concrete Society
NB - Norsk Betongforening / Norwegian Concrete Association
Polish Academy of Sciences, Committee for Civil Engineering, Poland
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Slovenian Society of Structural Engineers, Slovenia
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SB - Svenska Betongföreningen, Sweden
Délégation nationale suisse de la *fib*, Switzerland
TCA - Thailand Concrete Association
Laboratoire de Génie Civil (LGC), Université de Tunis El Manar, Tunisia
ITU - Istanbul Technical University, Turkey
NIISK - Research Institute of Building Constructions, Ukraine
Society of Engineers, United Arab Emirates
fib UK, United Kingdom
ASBI - American Segmental Bridge Institute, United States of America
PCI - Precast/Prestressed Concrete Institute, United States of America
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Precast insulated sandwich panels

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International Federation for Structural Concrete
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ISSN 1562-3610
ISBN 978-2-88394-124-3