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Prefabricated concrete sandwich and other lightweight wall panels for sustainable building construction: State-of-the-art review

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ABSTRACT

Prefabricated (or prefab) construction has become popular in recent years worldwide, owing to its advantages, including speed of construction, less wastage of materials, reduced labour demand, fabrication in a quality-controlled environment, and so on. Moreover, the current focus is on developing energy-efficient and sustainable buildings to reduce carbon emissions. To achieve this, prefab external wall panels that form the building envelope play a crucial role, as they maintain the indoor environment and thermal comfort and control the heating and cooling energy consumption, as well as the safety of the occupants of the buildings. Thus, the energy-efficient off-site fabricated building envelope significantly contributes to achieving net-zero targets in the construction sector set by the governments. An ideal prefabricated wall panel should be lightweight, eco-friendly, durable, fire-resistant, and easily installable. In addition, it should possess high strength, thermal resistance, and acoustic insulation. This study aims to review the most widely used external prefabricated wall panels in the building construction industry. Five types of prefab wall panels, namely, lightweight timber framed (LTF) panels, light-gauge steel-framed (LSF) panels, structural insulated panels (SIP), cross-laminated timber (CLT) panels and precast concrete sandwich panels (PCSP), which are commonly used for prefabricated building facades are reviewed with regards to their function, structural, thermal and fire performances, with an in-depth focus on the PCSPs. By reviewing the current research status and recent developments in materials, components, and structural performance of the PCSPs under various loading conditions, the current challenges and future work concerning the design of PCSPs and their applications in prefabricated construction are identified.

1. Introduction

Due to global warming, there is increasing interest in the development of sustainable infrastructure [1], which is challenging for the construction industry. Therefore, researchers and engineers globally are making enormous efforts to develop eco-friendly building materials and construction practices to meet the sustainability demand. Prefabricated (prefab) construction, also known as off-site construction (OSC), off-site manufacture (OSM), off-site fabrication (OSF), or industrialised building system (IBS), is a modern method of construction (MMC) [2] and has been identified as one of the viable methods for meeting sustainability requirements. Prefab construction offers several advantages, such as ease of construction, a shorter period of construction, reduced labour requirements, high-quality control due to prefabrication, and less wastage of materials compared to traditional in-situ construction methods

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[3–7]. Although prefab building construction technology has existed for more than 100 years [8], in the last decade, many countries, including Australia [3], Singapore [9], the UK [10], and China [11], have embraced and promoted the construction of new buildings using OSF technology, owing to the advantages of such construction methods over traditional construction methods.

Prefabricated construction is a broad term and, depending on the level of OSF, it can be classified into volumetric prefab construction (VPC) and non-volumetric prefab construction (NVPC) [12–16], as depicted in Fig. 1. In VPC, all the elements of a module, including beams, columns, floor and wall panels are assembled off-site with all the finishes, electrification, and plumbing, to form complete 3D modules [16–18]. The volumetric modules are then transported to the site for installation to form the complete modular structure, as shown in Fig. 2(a). In NVPC, depending on the design, off-site fabricated load-bearing wall and floor panels are connected at the site to construct the building structure (i.e., panelised prefab building), as depicted in Fig. 2(b). Alternatively, prefabricated beams and columns may be assembled together with floor and non-load bearing façade panels to construct a framed prefab building, as illustrated in Fig. 2(c). Hybrid prefab construction (HPC) (also known as semi-volumetric construction) refers to construction that combines VPC and NVPC [12]. NVPC and HPC offer greater flexibility and customisation, compared to VPC, and faster construction than traditional in-situ construction methods [12]. Therefore, hybrid prefab methods have been adopted for the construction of many prefabricated buildings [5].

The construction industry accounts for about 35 % of the global energy demand and 38 % of the global carbon emission from that energy production and process [20]. Hence, considering the United Nation's (UN) sustainable development goals (SDG), the world green building council (WGBC) has introduced a global programme “Advancing Net-Zero” aiming towards total sector decarbonisation by 2050. Meanwhile, the WGBC's 2030 target is to make all the new buildings net-zero operational carbon with at least 40 % less embodied carbon [21]. Therefore, focusing on net-zero carbon emission, many developed countries have introduced stricter thermal resistance requirements for building envelopes to reduce the heating and cooling energy demands of the buildings. Due to higher sustainability requirements throughout the world, it is essential to develop the components of the buildings to be durable and structurally robust using eco-friendly materials [1], as well as to adopt energy efficiency measures. In both the methods of prefab construction discussed above, prefabricated wall panels are the important elements (sub-component in VPC and component in NVPC) constituting a significant portion of the building in the form of external facades and internal partition walls [22] and can either be load-bearing or non-load bearing depending on the design requirements and types of construction. In buildings, heating, ventilation, and air conditioning (HVAC) systems consume almost 38 % of energy [23]. The external wall panel or façade which forms the building envelope, is one of the significant components of the building in contact with the outside environment, contributing to the indoor climate and has a considerable impact on the thermal efficiency or energy demand of the building, as well as the comfort and safety of the occupants [12]. A variety of external wall panels have been widely used in the building construction industry. However, the application of precast concrete sandwich panels (PCSP) for building envelopes has gained more and more attention recently by researchers and the industry.

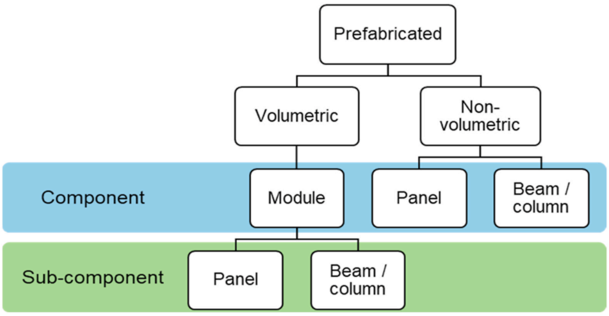


Fig. 1. Classification of prefabricated construction.

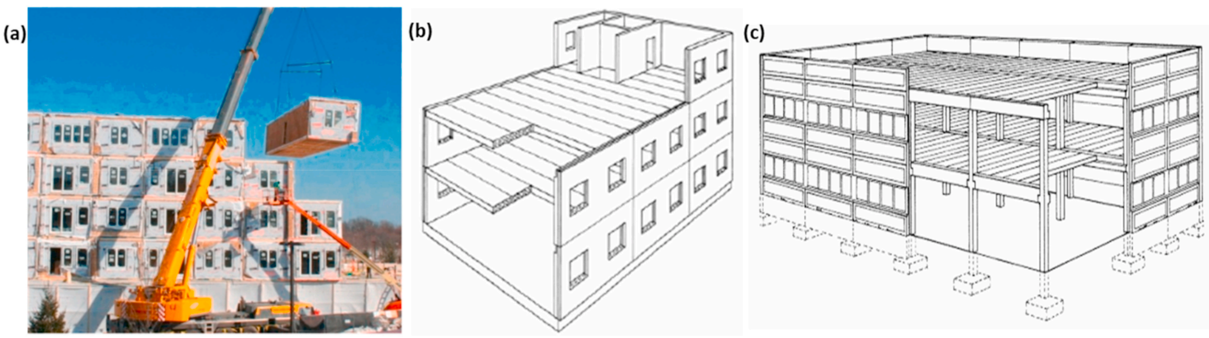


Fig. 2. (a) Volumetric prefab building [4], (b) Panelised prefab building [19], (c) Framed prefab building [19].

In the last few years, several researchers have highlighted the thermal and structural benefits of precast concrete sandwich panels (PCSP) in their review papers. Yu et al. [11] presented a detailed review of the thermal performance of the PCSPs and their significance in reducing carbon emissions in the building construction industry of China. Amran et al. [24] provided a comprehensive review of the structural insulated panels with a focus on PCSPs and their structural, thermal, and acoustic performances. Furthermore, their study concluded with suggestions for developing PCSPs using lightweight concrete (LWC) and a greater number of shear connectors for enhancing composite action. Similarly, Tawil et al. [25] reviewed the structural and thermal performances of the PCSPs and suggested further research on PCSPs utilising LWC and more shear connectors for better composite action. Another review paper by Hegarty and Kinane [26] provided detailed information on the thermal and structural behaviour of thin and lightweight PCSPs suitable for cladding or facades in buildings. However, due to the existence of various types of prefabricated wall panels in the construction industry, having their own merits and demerits, it is necessary to review the performance and application of those panels, compare them and then recommend further improvements in their manufacturing, design, and installation, which has been lacking in the existing studies. Also, the review of composite PCSPs and their connections for structural load-bearing applications in prefabricated construction is still lacking.

This study presents a review of various types of prefabricated wall panels used in prefab building construction (particularly in panelised construction). Firstly, five different types of popularly used prefabricated wall panels, namely, lightweight timber framed (LTF), lightgauge steel framed (LSF), structural insulated panel (SIP), cross-laminated timber (CLT), and precast concrete sandwich (PCSP) panels are reviewed. Then, a detailed review of PCSPs, including their components, structural performance under various types of loads (flexural, compression, impact, blast, racking and fire, etc.), and connection methods is presented. In addition, the research on the thermal performance of the PCSPs is discussed. Lastly, the analytical methods and numerical modelling for the design of PCSPs are reviewed, and recommendations for future works on several key research areas related to composite PCSPs for improvement are suggested.

2. Types of prefabricated wall panels

External walls are important building components, and the design of such walls considers several factors, including strength, durability, safety, thermal resistance, air and moisture management, acoustic performance, fire resistance, aesthetic appearance, and cost, in addition to sustainability in modern construction. Also, the method of construction (i.e., VPC or NVPC) and height (low-rise, mid-rise, and high-rise) needs to be taken into account, which could affect the selection, planning and design of the wall panels as structural and non-structural components. In this study, buildings of one to three storeys, four to eight storeys, and nine to nineteen storeys are categorised as low-rise, mid-rise and high-rise buildings, respectively [27]. In practice, there are numerous products commercially available. However, as illustrated in Table 1, five types of prefabricated wall panels that are widely used as external walls in prefab building construction, i.e., LTF, LSF, SIP, CLT, and PCSP panels, are reviewed in this study.

2.1. Lightweight timber framed (LTF) panel

Timber frames have been widely used for residential buildings, and timber stud frames were historically used in wall panels for prefab construction [17], owing to their lightweight and low cost of construction [28]. The panels typically consisted of timber studs, and top and bottom timber grids (or plates) with oriented strand board (OSB) sheathing board or gypsum plasterboard attached to the external and internal faces (Fig. 3 (a)) using screws and nails. An insulation material is placed in between the timber studs, as presented in Fig. 3(a). Fig. 3(b) depicts the construction of a panelised prefabricated building with timber-framed walls (before the installation of insulation and sheathing board). Since timber is a renewable resource, LTF panels are environment-friendly and contribute to achieving the net-zero target set by the world green building council (WGBC). LTF also offers significant reduction in the embodied carbon and building load compared to LSF [29]. Although there is increasing interest towards timber materials used for building construction, some of the structural and physical properties of the timber material pose certain constraints on its wide application [30]. LTF panels have been widely used in low-rise buildings, as shown in Fig. 3(b). Nonetheless, their application is limited in

Table 1
Prefabricated wall panel types reviewed in this article.

Wall panel types	Function	Advantages	Disadvantages
Lightweight timber framed (LTF)	Load-bearing in low-rise and non-load-bearing in mid to high-rise buildings	Lightweight, easy to fabricate, cost-effective, renewable resource	Susceptible to mould and termite, low fire resistance, durability issues with exposure to moisture, low blast resistance
Light gauge steel framed (LSF)	Load-bearing in low to mid-rise and non-load-bearing in high-rise buildings	Easy fabrication, high strength-to-weight ratio, resistance to mould and termite, good fire resistance, low embodied carbon	Corrosion of steel studs, thermal bridging effect, low blast resistance
Structural insulated panel (SIP)	Load-bearing in low-rise and non-load-bearing in mid to high-rise buildings	High strength-to-weight ratio, high thermal insulation, economical, low embodied carbon	Low fire resistance, durability issues, low impact and blast resistance
Cross-laminated timber (CLT)	Load-bearing in low to mid-rise and non-load-bearing in high-rise buildings	High strength, thermal insulation, renewable resource	Durability issues, low fire resistance, high cost
Precast concrete sandwich panel (PCSP)	Load-bearing and non-load-bearing in low to high-rise buildings	High strength, durable, fire resistant, high thermal insulation, low maintenance cost, low operational carbon	Wet connection, corrosion of steel reinforcement

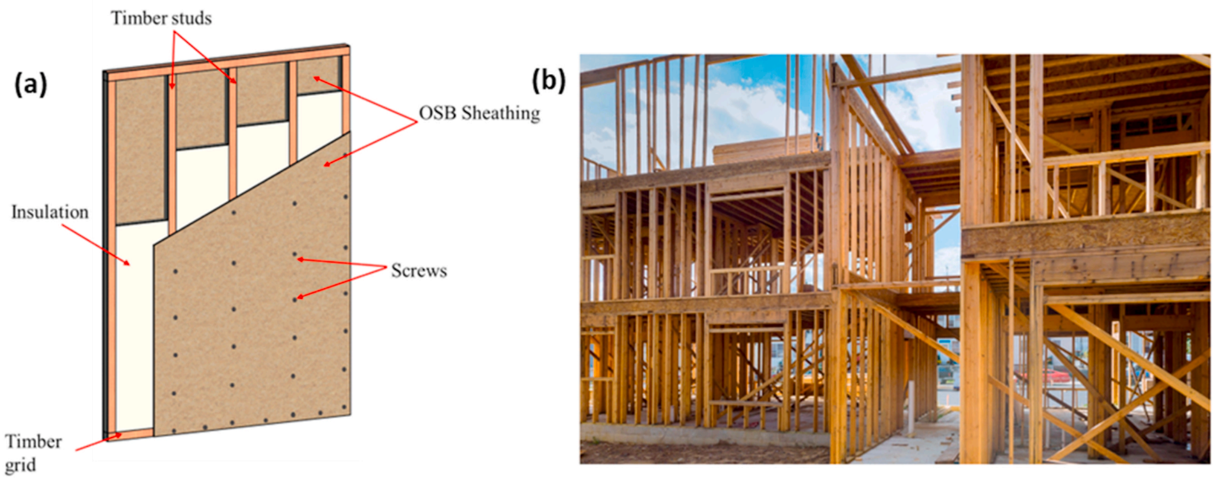


Fig. 3. (a) Lightweight timber-framed wall panel, (b) Erection of lightweight timber-framed wall panels [36].

multi-storey buildings due to lower compression resistance perpendicular to the grain as well as short and long-term shortenings [31]. The height of stacked timber modules (where LTF walls act as load-bearing) is generally limited to four-storeys [17]. However, if installed within a primary structural frame, i.e., as a non-load-bearing wall, it can be considered in the construction of mid-rise and high-rise prefabricated buildings [32]. Load-bearing LTF panels are also designed to resist in-plane lateral shear [33]. The timber material is relatively easy to shape, and the stud frame construction is flexible [34]. However, the timber is vulnerable to fire and deterioration due to mould and termites in case of exposure to moisture [32], which makes it less popular than steel and concrete [17]. In addition, from the experimental investigation, the failure of the LTF panels under blast loading was observed to be severe with blowout of the sheathing and cracking of the studs [35], which might make it unfavourable for essential or critical buildings. More information on the blast performance of the LTF panels can be obtained in Ref. [34].

2.2. Light-gauge steel framed (LSF) panel

The steel stud frame (Fig. 4(a)), which is similar in construction to LTF except the timber studs are replaced with steel studs, has been preferred over timber owing to the speed of construction and cost benefits in some cases [32]. As presented in Fig. 4(a), the LSF panel consists of cold-formed steel (CFS) studs connected to surrounding tracks using screws, with insulation in between the steel studs, and external and internal plasterboards. Fig. 4(b) demonstrates the construction of a building using prefabricated LSF wall panels. Compared to timber, steel frames are durable and strong, and have better fire resistance [37]. In addition, LSF panels have lower embodied energy than conventional construction systems such as reinforced concrete and structural steel [38]. The embodied carbon assessment of light steel framing and timber framing with various cladding systems showed that LSF with insulated render possesses about 60 % less embodied carbon compared to brickwork and terracotta cladding [39]. LSF walls have many advantages, including resistance to mould and termites, high strength-to-weight ratio, easy fabrication, and easy installation [37] and are widely used as load-bearing walls in low-to mid-rise and non-load-bearing walls in high-rise buildings [40], respectively. Furthermore, LSF walls are more suited (than timber framed walls) to advanced manufacturing and automation of manufacturing, e.g., Howick roll forming [41],

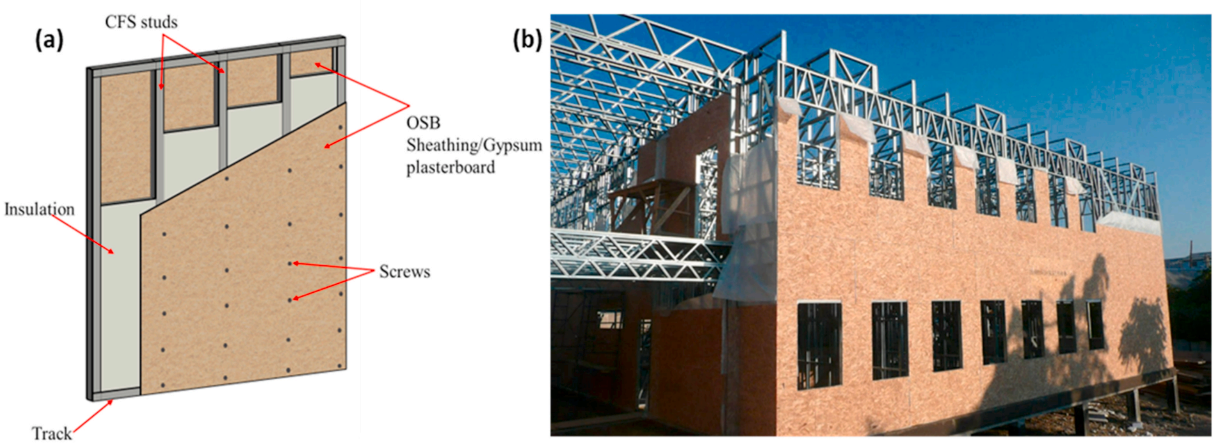


Fig. 4. (a) LSF wall panel, (b) Construction of office building using LSF wall panels [49].

Voestalpine roll forming [42], etc. Nevertheless, there are some disadvantages, such as corrosion of the steel studs and screws when exposed to moisture, and thermal bridging due to the high conductivity of the steel studs [43], which demands an additional thermal barrier [44]. Researchers are making efforts to overcome these issues. For instance, Yang et al. [45] introduced an LSF wall with slotted studs to reduce the thermal bridging. Liu et al. [46] developed a demountable LSF wall consisting of an insulation frame to improve thermal performance by reducing the thermal bridging effects of steel studs. For more details on the LSF panel, its thermal performance and strategies to minimise thermal bridging, readers may refer to Ref. [43]. Furthermore, the inadequate fire protection of the CFS studs may result in quick heating of the studs that could reduce their strength and stiffness [44]. Therefore, various methods such as double layer of gypsum plasterboard [40], double stud wall [44], staggered stud wall [44], and square and rectangular hollow studs [47] were investigated to improve the fire resistance and enhance the loading capacity of LSF wall panels. LSF panels also offer limited blast resistance due to the development of premature buckling instabilities in studs [48]. Although LSF walls are lightweight, they can become heavy with the required cladding, insulation, thermal barriers, and fireproofing. The thickness of insulation is also limited to the depth of steel studs and sometimes requires a double-layer LSF wall to meet the requirement of thermal and fire resistance [44].

2.3. Structural insulated panel (SIP)

Structural insulated panels (SIP) are a type of prefabricated sandwich panel which is widely used in the construction industry as a floor, roof, and wall component of the building. These panels have some advantages over timber framed and light steel frame wall panels, particularly with regard to thermal performance. SIPs do not have any studs in between the external sheathings, eliminating the issue of thermal bridging effects [50,51]. Moreover, SIPs are lighter in weight, enhancing their appeal for prefabricated construction. As shown in Fig. 5(a)–a typical SIP comprises an insulating foam core sandwiched between two thin skins of OSB (oriented strand board), connected using adhesive/glue, and is mostly used in the prefabricated construction of low-rise residential housing (typically one to two stories, as shown in Fig. 5(b)) in the form of a load-bearing wall. Due to their limited structural capacity, SIPs are only suitable as non-load-bearing walls for mid-rise and high-rise buildings. SIPs offer greater freedom in insulation thickness compared to light steel framing (where insulation thickness is linked to steel stud depth). SIPs are suitable for automation through panel production lines like Gluestream [52]. Skin glued to foam core, or foam injected between skins, allows more efficient manufacturing of SIPs than light steel frames, which require greater handling to weld/screw/rivet the frame and cladding. In addition, SIP was observed to have lower embodied carbon emissions than LTF and LSF offering economical building solutions in a case study [53].

Owing to SIP's energy efficiency due to thermal insulation and the potential to achieve net-zero carbon [55], buildings constructed using SIPs are often called green buildings [24]. However, the OSB sheets of SIPs have a low tolerance to moisture and fire [24]. In addition, Amran et al. [24] mentioned the problematic reactiveness of adhesive strips in OSB and the possible degradation of OSB due to white ants. Other materials for external layers of SIP have been investigated in the past (as listed in Table 2) to overcome the problems of OSB. Smakosz and Tejchman [56] used magnesia cement boards owing to their improved mechanical properties and smooth external surface compared to OSB. But water infiltration and the freezing-thawing process could be significant issues if not adhered to high-quality control during fabrication. Magnesium Oxide (MgO) boards for facing in SIP were used by Manalo [57], considering low energy consumption, high strength, and resistance to mould and mildew. In addition, several SIPs have been developed using different materials, such as glass fibre reinforced polymer (GFRP) skin [58], basalt fibre reinforced polymer (BFRP) skin [59], and flax fibre reinforced polymer (FFRP) skin [60] (refer to Table 2). However, those panels have merits and demerits and must be carefully considered before adopting them for building constructions. For instance, GFRP skin [58] and FFRP skin [60] contribute to high flexural resistance, owing to the high tensile strength of GFRP and FFRP, respectively. The fire-exposed GFRP or FFRP surface, however, might result in poor performance. Also, debonding between GFRP skin and polyurethane (PUR) foam and FFRP and polyisocyanurate (PIR) foam was observed in flexural tests [58,60]. Similarly, steel skin enhances the structural performance of the SIPs, but high thermal conductivity of the metallic skin could reduce the thermal resistance compared to other composite materials [61]. The performance of SIP has been investigated especially against windborne debris impact, which revealed the vulnerability and failure behaviour of the SIP panels with different types of skin, including steel [62,63], OSB [64], fibre cement board [64], OSB strengthened by glass fibre laminate [65], and basalt fibre cloth [66]. SIP panels with steel and OSB sheathings also showed poor blast resistance [67,68]. Re-

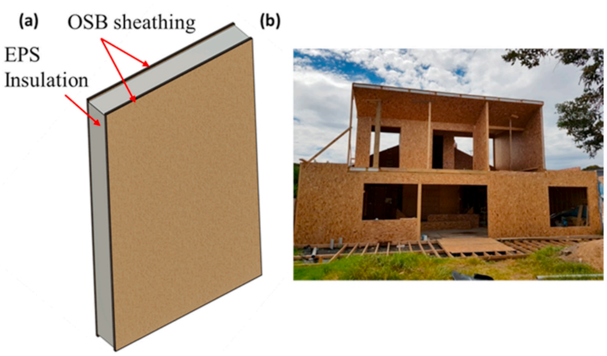


Fig. 5. (a) Structural Insulated Panel, (b) Construction of house with SIPs [54].

Table 2
Review of structural insulated panels (SIPs).

Ref	Skin types	Core types	Advantages	Disadvantages
[68,73, 74]	OSB	EPS/PIR/PUR	Availability, large size panel [24]	Susceptible to termite attack, durability, moisture penetration, low fire resistance, aesthetic appearance [75]
[75,76]	Glass/poly-propylene sheets	Polystyrene	Low-cost, high-strength, durable [76]	Low fire resistance [77]
[56,57, 78]	MgO board	GFR-PUR/EPS	Resistance to mould and mildew, smooth external surface, fire resistant [56,57]	Water infiltration, freezing-thawing process, availability, and limited panel size [24,56].
[63]	Steel	EPS	High-strength, fire resistant, resistant to mould and mildew, lightweight, long length possible from coil stock [24]	Corrosion issue, aesthetic appearance
[60]	FFRP sheet	PIR	Good strength, lightweight, cost-effective [79]	Low fire resistance, highly hydrophilic, durability issue due to moisture [80]
[81,82]	Cement fibreboard	EPS/EPS-FC	Moisture resistance, fire resistance, resistance to mould and mildew, aesthetic appearance [81]	Brittle, low tensile strength, handling and installation difficulty, limitation on the panel size [24]
[59]	BFRP sheet	PUR/XPS/RW/ PUR + RW/ XPS + RW	High strength, corrosion resistance, low thermal conductivity [83]	Low fire resistance [84]
[85]	GFRP/GFRC	EPS	High strength, durable, low thermal conductivity [24]	Low fire resistance [24]
[51]	Plywood	PUR	Good strength [51]	Availability, moisture absorption, low fire resistance, susceptibility to termite attack, limited panel size [24]
[83]	FRG sheet	PUR	Durable, resistant to mould and termite, fire resistance [83]	Debonding issues [83]

Note: Refer to Table 4 for the acronyms of corresponding insulation.

cently, a composite SIP with environmental-friendly fibre-reinforced geopolymer (FRG) sheets was developed, which exhibited good strength but debonding between foam core and external sheathings was observed during compression tests [69].

In Australia, the use of expanded polystyrene (EPS) products (common in SIPs) in an external insulation and finish wall system in multi-storey buildings has been prohibited [70,71]. Likewise, the use of combustible materials with a rating of less than A2 in the construction of domestic buildings with a height of more than 18 m is prohibited in the UK [26]. Therefore, there is a growing interest among researchers and industries for further development in SIPs for prefabricated buildings, especially for mid-rise and high-rise that could satisfy the overall requirements, including structural, fire, thermal and acoustic performances. At the same time, it must be eco-friendly, lightweight, durable, and easy to install.

In current practice, the connections among SIPs, periphery tracks, floor, and roof are made using nails and screws or glue, and the design guidelines have been developed accordingly [72]. The connections between panels and the main structure (e.g., steel frame) might be more difficult and crucial for structural integrity. No specific guidelines are available for such connection of SIP system and could be worthy of further research to promote the use of SIP as non-load-bearing walls in multi-storey buildings.

2.4. Cross-laminated timber (CLT) panel

CLT panel is another kind of prefabricated panel made up of timbers in multiple layers oriented in a perpendicular orientation and bonded using adhesives to form a solid, straight, rectangular panel, as shown in Fig. 6(a). CLT panels have been used for the construc-

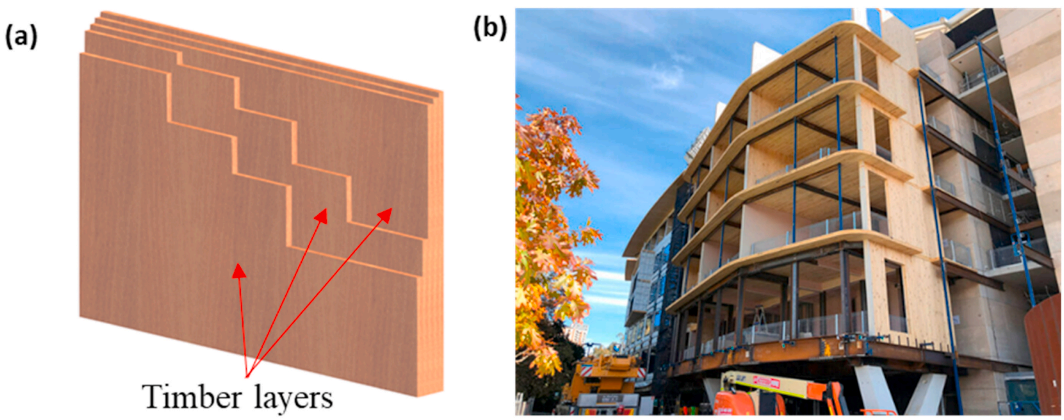


Fig. 6. (a) CLT panel, (b) Construction of Adelaide Oval Hotel using CLT floors and walls [93].

tion of houses since the early 1990s [86]. CLT panels in the form of walls and floors are found to be increasingly used in prefabricated buildings, as depicted in Fig. 6(b). The construction of buildings using timber products is considered highly eco-friendly and energy-efficient compared to steel and concrete, as it is a renewable resource and carbon-neutral material [32]. In recent years, the construction of buildings using timber has gained attention throughout the world to tackle the environmental issues posed by construction materials like concrete and steel. The LCA study revealed that replacing steel or concrete with CLT can reduce carbon footprint by about 40 % for a multi-storey building [87] and provide superior energy savings in comparison to concrete structures [88]. CLT panels have high strength and thermal resistance, and are suitable for load-bearing walls [11] in multi-storey buildings to resist horizontal shear and axial compression forces [89]. Nonetheless, CLT panels have some significant drawbacks, including low fire resistance and deterioration due to moisture [88], which prevent them from being widely adopted in high-rise construction and possibly for volumetric prefab construction where fires through voids of modules could be hazardous. CLT panels are also heavier compared to LTF, LSF, and SIP panels [11].

The cost of CLT construction is higher compared to concrete construction [90]. Due to the rising interest and recent developments in mid-rise and high-rise mass timber construction, the International Building Code (IBC 2021) and the National Building Code of Canada (NBCC 2020) have increased the limit on the building height of timber structures to 18 and 12 stories, respectively [91]. In Australia, considering the fire resistance and stability of the structure, the construction of fire protected timber buildings has been limited to a maximum height of 25 meters or eight stories as per the National Construction Code (NCC) of Australia [71]. However, building developers have the flexibility to go beyond 25 meters of height, provided they can satisfy all the essential safety requirements by devising their own methods, which might be the reason for the reluctance of the developers. Readers may refer to Ref. [92] for detailed information on CLT manufacturing, design and construction.

2.5. Precast concrete sandwich panel (PCSP)

PCSPs were developed more than 70 years ago [94] to overcome the thermal insulation shortcomings of solid precast concrete panels. Although some researchers refer to PCSP as SIP [24], it should be noted that SIP may have inner and outer layers made of various materials, as explained in section 2.3. In contrast, PCSP has both inner and outer layers made of concrete material that makes it unique and distinctive as its name (precast concrete sandwich panel) implies. As depicted in Fig. 7, an insulation layer is sandwiched between two concrete layers (also known as concrete wythes) and connected using mechanical shear connectors to form a three-layered sandwich panel. Owing to its high strength, multi-hazard resistance, durability, sustainability, energy efficiency, and versatile aesthetic properties, PCSP is preferred for building facades in prefabricated construction in the form of load-bearing and non-load-bearing walls [95], as illustrated in Fig. 8. As compared to other prefabricated panels, the heavier weight of the PCSP also makes it suitable for specialist facilities such as laboratories and hospital operating theatres, for which vibration criteria could be more easily satisfied due to the greater mass of the building [17]. In addition, owing to the high thermal mass of concrete, the peak heating and cooling loads for PCSPs are 13 % and 30 %, respectively, lower than those for LSF or LTF panels having the same U-values [96]. Studies on the life cycle assessment (LCA) of building façades using PCSPs revealed that PCSP can reduce operational emissions over the service life of the building compared to traditional brick veneer wall [97] and solid precast concrete panels [98], which aligns with the WGBC 2030 target. The LCA outcomes also exhibited a substantial reduction in embodied carbon emission and energy demand when fly ash is used in the production of PCSPs [97]. Furthermore, prefabricated concrete structures can help reduce construction wastes and conserve resources, since they can provide a hundred year service life or more, as well as be re-used as crushed aggregate for concrete mix, pavement construction, and backfill at the end of service life [97]. The examples of PCSPs for VPC and NVPC prefabricated building are presented in Fig. 9.

Depending on the performance of the shear connectors in developing composite action between the two concrete wythes, PCSPs are classified into two types, namely, non-composite and composite PCSPs. Fig. 10 shows the difference between non-composite and composite PCSPs, while Fig. 11 depicts the strain distribution in the PCSPs with varying levels of composite action (i.e., fully-composite, non-composite, and partially composite). The greater degree of composite action leads to smaller strains (Fig. 11(a)), which allows the use of thinner sections for a given loading (Fig. 10(a)), compared to non-composite thicker sections (Fig. 10(b)) with low (or negligible) degree of composite action with large strains (Fig. 11(b)). However, in practice, most of the PCSPs behave as partially composite (somewhere in between fully composite and non-composite, as shown in (Fig. 11(c)) due to inevitable slip between

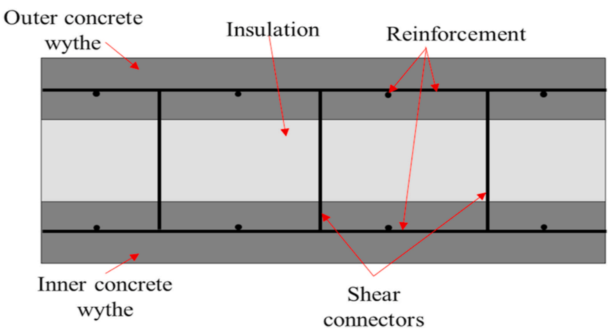


Fig. 7. Precast concrete sandwich wall panel.

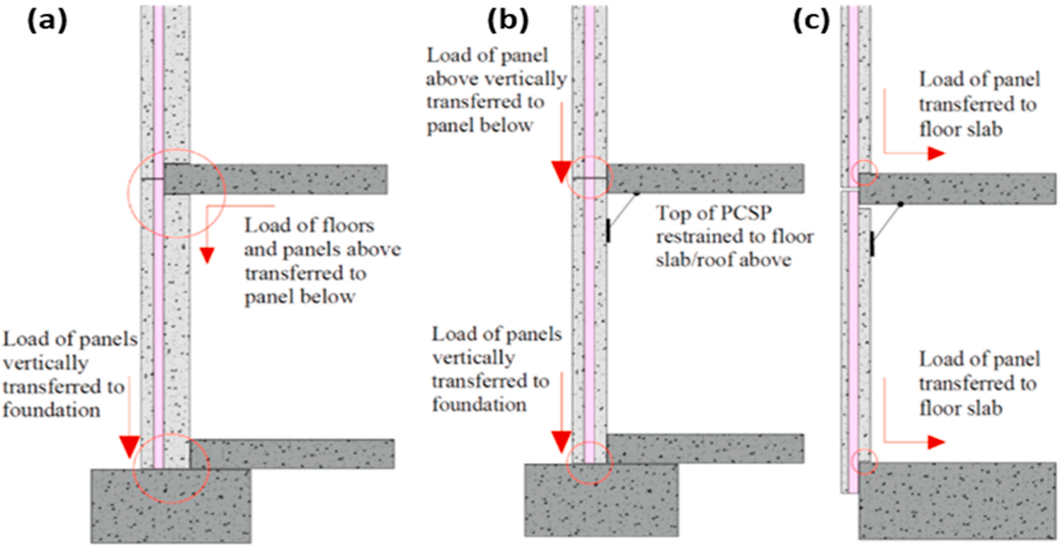


Fig. 8. Types of construction using external PCSP walls (a) & (b) load-bearing, (c) non-load-bearing [26].

Fig. 9. Prefabricated buildings using PCSPs (a) VPC [99], (b) NVPC [100].

the two concrete wythes, unless both ends of the panels are designed with solid concrete edges to prevent the slip [101] which is not desirable.

In non-composite PCSP (Fig. 10(b)), the inner concrete wythe is the structural wythe similar to a solid precast concrete panel and is designed to support the vertical and lateral loads, while the external layer acts as cladding and protects the insulation layer. The shear connectors are designed mainly to transfer the weight of the external wythe to the internal wythe, as well as to resist tension, compression, and seismic forces, as shown in Fig. 12. In composite PCSP (Fig. 10(a)), both inner and outer wythes are designed to carry the structural loads through composite action developed in between using shear connectors [102]. That is why shear connectors for PCSPs were also classified into non-composite and composite shear connectors for non-composite and composite PCSPs, respectively [96].

The composite PCSPs can achieve up to 100 % composite action in flexure [105], and nearly 80–90 % axial load carrying capacity in compression compared to that of solid wall panels [106,107]. On that basis, it is interesting to note from Fig. 10 that 200 mm thick composite and 300 mm thick non-composite PCSP types possess approximately equivalent structural capacity (axial and bending) compared to 200 mm thick solid precast concrete panels [103]. This demonstrates that composite PCSP can provide high load-bearing capacity using less concrete and are about 25 % and 40 % lighter compared to solid concrete wall and non-composite PCSP, respectively. In terms of thermal performance, it is similar to non-composite PCSP, while it provides higher thermal resistance than solid concrete panel, due to the presence of continuous insulation layer. Moreover, composite PCSPs offer economic benefits due to a reduction in material usage, and a reduction in transportation, lifting, and handling costs compared to non-composite PCSPs [103]. Despite composite PCSPs offering significant advantages over non-composite PCSPs, their application was found to be limited compared to non-composite PCSPs [95]. Some of the main reasons behind this might be the lack of appropriate knowledge on the structural performance of the composite PCSPs, lack of proper design guidelines, complex and proprietary design of shear connectors as

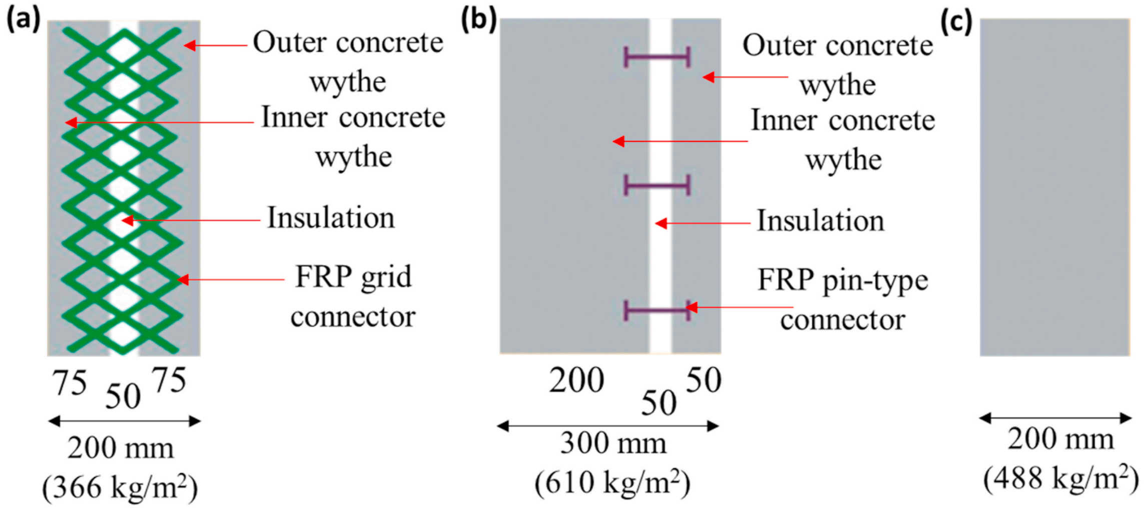


Fig. 10. (a) Composite PCSP, (b) non-composite PCSP, and (c) solid panel with roughly equivalent structural capacity (*Note: The dimensions for composite PCSP, non-composite PCSP and solid panels (i.e.,* 200 mm, 300 mm *and* 200 mm, *respectively) are indicative values giving some comparable axial and bending strength. All the concrete layers have reinforcement, which is omitted here for clarity*) (adapted from Ref. [103]).

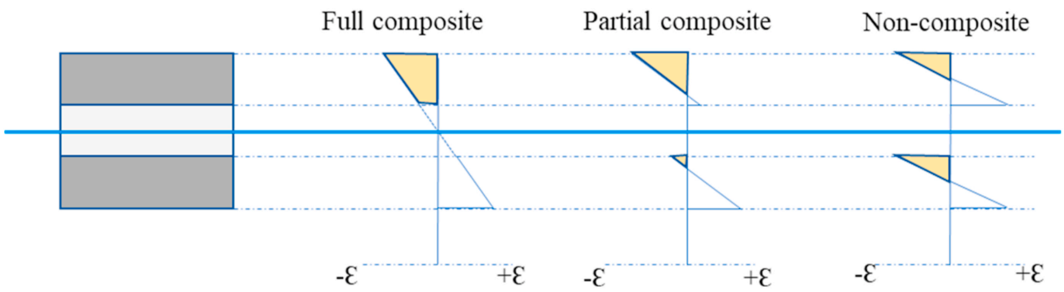


Fig. 11. Degree of composite action displaying approximate strain distribution in PCSPs (based on [26]).

the majority of composite shear connectors were developed and tested confidentially, and reliance on the shear connectors capacity provided by the manufacturer of the connectors [95,108]. Other reasons may include the lifting, bracing, and connection difficulties due to the thin concrete wythes of composite PCSPs, whereas in non-composite PCSPs all the lifting, bracing, and connection components are installed into an inner thick layer that is similar to the traditional precast concrete panels. These current challenges prevent the proper utilisation of the strength, materials, and low-cost benefits of composite PCSPs.

The composite action between concrete wythes and the insulation layer is one of the challenging issues in utilising the full strength of the composite PCSPs. The inadequate design of connectors can lead to severe failure of the PCSP, as observed in Fig. 13(a) and (b). On the other hand, the material of shear connectors significantly affects the thermal performance of the PCSPs through thermal bridging. As a result, enormous effort has been made towards improving the composite action and thermal performance using a variety of shear connectors. Moreover, researchers have explored the utilisation of different types of concrete to improve the strength and reduce the thickness and weight of the panels. Table 3 summarises the developments in the PCSPs (both composite and non-composite types), considering the materials used for the concrete layers, insulation, and shear connectors, and tests performed (based on the references reviewed in this study).

2.5.1. *Concrete wythes in PCSP*

Concrete wythes are the crucial component of the PCSPs for resisting loads, and they can be either load-bearing or non-load-bearing. Here, load-bearing refers to the wythes and/or panels which are subjected to vertical loads from the upper storeys (Fig. 8(a) and (b)), while non-load bearing refers to a wythe and/or panel that does not support any vertical loads other than its self-weight (Fig. 8(c)). Both load-bearing and non-load-bearing wythes and/or panels may be subjected to other in-plane and out-of-plane horizontal loads, including wind and seismic, as presented in Fig. 12. The thickness of concrete wythes varies depending on the applied load, anchorage depth of the shear connectors, cover to the reinforcement, and fire resistance, which could be designed with thickness from as low as 25 mm to more than 150 mm, as illustrated in Table 3. For load-bearing panels, the thickness of concrete wythes is typically 50–75 mm, as observed from Table 3 for the composite PCSPs evaluated for axial compression performance. External concrete layers can further be utilised to optimise the energy efficiency of the building by integrating new solar technology [109].

The traditional PCSPs were usually comprised of wythes of normal concrete and steel reinforcement [96]. However, with the advancement in concrete technology and higher sustainability demands, several types of green concrete, including geopolymer concrete

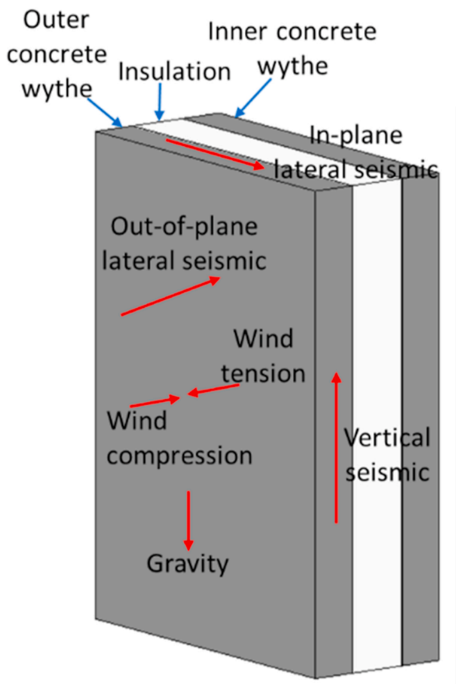


Fig. 12. Forces acting on the external concrete wythes of PCSPs (generated based on [104]).

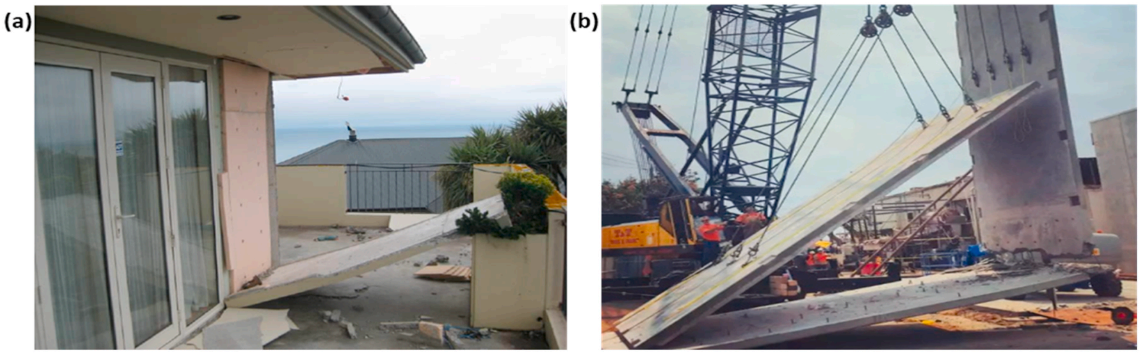


Fig. 13. Failure of precast concrete sandwich wall panels (a) during earthquake [166], (b) during construction [167].

[110,111], foamed concrete [112], recycled aggregate concrete [113], and textile-reinforced concrete [114] were explored to produce eco-friendly PCSPs (refer to Table 3). In addition, high-strength concrete (up to 80 MPa) [115] and ultra-high-performance concrete (UHPC) [116] were employed to enhance the strength and reduce the thickness and weight of the panels. On the other hand, the corrosion of steel was observed as a problem in reducing the durability and maintenance cost of the precast concrete claddings [117,118]. The fibre-reinforced polymer (FRP) rebars may offer a viable solution to tackle the corrosion issue of steel rebars, which has been extensively investigated in the literature for reinforced concrete (RC) structural components. Since PCSPs are widely used as external walls in prefabricated buildings, some efforts in recent years were made by researchers [105,110,111,119,120] to replace the steel rebars with basalt FRP (BFRP) reinforcement in concrete wythes of PCSPs, which revealed the potential application of FRP rebars in PCSPs. However, the studies were limited to static behaviours of the panel investigating limited parameters. Further research into the static and dynamic behaviours of PCSPs with BFRP reinforced concrete wythes would be necessary in developing design guide and promoting the wide application of such PCSPs.

2.5.2. Shear connectors in PCSP

Shear connectors are another crucial component in maintaining the desired thermal and structural performance of the PCSPs, as mentioned previously. Shear connectors are divided into two main types: non-composite and composite shear connectors. The functions of non-composite shear connectors are to resist tension and compression forces arising from out-of-plane lateral wind pressure and suction, seismic pressure, and form suction during the lifting of the panels, as well as to resist shear and bending from the weight of the external non-structural wythe along with vertical and in-plane seismic actions (Fig. 12). The function of the composite shear connectors is to hold both internal and external concrete wythes together to resist any vertical and lateral loadings by developing

Table 3
Summary of materials and tests in PCSPs research.

Ref.	Type of concrete	Reinforcement type	Insulation type	Shear connectors	Tests performed	t_{ext} (mm)	t_{int} (mm)	t_{ins} (mm)	Panel type
[113]	RAC	Steel	EPS	BFRP bars	Double shear/Four-point bending	60	60	170–270	CP
[121]	NC	Steel	XPS	BFRP bars	Double shear	60	60	100	–
[122]	NC	Steel	XPS	Vierendeel truss-like/ star shaped/ductile shear ties made of GFRP	Single shear/Double shear	75	75	50–100	–
[123]	NC	Steel	XPS	Steel/GFRP/Polymer	Double shear	51	51	152	–
[124]	NC	Steel	XPS	Thermomass NC series connectors	Double shear	60	90	30	–
[125]	NC	Steel	EPS	Flat steel plates	Double shear	60	60	30–120	–
[126]	SCC	–	EPS	CFRP grid	Double shear	50	50	50–150	–
[127]	NC	Steel	XPS/EPS	Corrugated GFRP	Double shear	60–80	60–80	100	–
[128]	NC	Steel	EPS	Flat steel plate	Single shear	70	120	240	–
[129,130]	NC	Steel	EPS/XPS/PIR	Nu tie, Thermomass CC and X-series connectors, HK Ca ties	Double shear/Six-point bending	76–100	76–100	76–100	CP
[131,132]	NC	Steel	XPS	W-shaped steel-GFRP composite	Single shear/Four-point bending	55	55	50–80	CP
[104]	NC	Steel	_	C-shaped GFRP	Double shear	60	75	60–300	–
[133]	NC	Steel	XPS	GFRP flat plate, corrugated plate, hexagonal tube	Double shear	75	75	50	–
[134]	NC	Steel	_	I-shaped GFRP	Double shear	60	75	60–300	–
[135]	NC	Steel	EPS	Hybrid GFRP/steel cages	Four-point bending	64	64	76	CP
[136]	NC	Prestressing steel strands	EPS	Steel truss	Flexural test under uniform pressure/cyclic three-point bending/ Double shear	76	76	50.8	CP
[137]	Foamed LWC	Steel	Mineral-hydrated foam	Threaded steel rods	Four-point bending	100	100	150	CP
[138]	NC with vitrified microspheres	Steel	Graphite polystyrene	Dumbbell-shaped steel-FRP composite bar	Four-point bending	60	120	130	NCP
[114]	TRC	–	FC	GFRP plate and pin	Four-point quasi-static and cyclic bending	30	50	150	NCP
[139,140]	NC	Steel	EPS + Polystyrene grooved board	Z-shape steel plates	Double shear/Four-point bending	76	76	76	CP
[141]	NC	Steel	EPS/XPS	GFRP shear grid	Monotonic and cyclic four-point bending	60	100	60	CP
[142]	NC	Steel	EPS	Segmental GFRP plates	Three-point bending	25–76	76	102	CP
[143]	NC	Steel	XPS	C-shaped GFRP, steel truss	Four-point bending	76	76	127	CP
[144]	CC	Steel	PUR	Flat steel plate + pin type	Four-point bending	60	120–150	70–100	NCP
[145]	NC	Steel	EPS	Steel truss	Uniformly distributed load bending test	25	25	100	CP
[146]	NC	Steel	XPS/EPS	Ductile shear tie system	Flexural test under uniform pressure	76.2	76.2	50.8	CP
[101]	NC	Prestressing steel strands	XPS	Steel M-tie and concrete	Flexural test under uniform pressure	76	76	51	CP/ NCP
[116]	UHPC	Steel	XPS	Concrete studs	Four-point bending	20–30	20–30	90–110	CP
[147]	NC	Steel	XPS	GFRP grating	Double shear/Four-point bending	50–75	50–75	50–250	CP
[148]	NC	Steel	XPS	Thermomass NC series connectors	Direct tensile/Double shear/Four-point bending	60	60–100	50	NCP
[149]	NC	Steel	EPS/XPS	GFRP shear grids	Four-point bending (negative and positive)	60	60	100	CP

(continued on next page)

Table 3 (*continued*)

Ref.	Type of concrete	Reinforcement type	Insulation type	Shear connectors	Tests performed	t_{ext} (mm)	t_{int} (mm)	t_{ins} (mm)	Panel type
[150]	HPFRC	–	VIP + phenolic foam	CFRP lattice	Three-point bending	25–40	40	90	CP
[107]	NC	Steel	EPS	Vierendeel truss-like shear connectors made of GFRP	Four-point bending/ Eccentric compression	65	65	50	CP
[151]	SCC	Steel	Recycled tire crumb rubber	Steel tie bars	Concentric compression	40	40	20	CP
[152]	SC	Steel	Corrugated polystyrene	Steel wire	Concentric, eccentric, and diagonal compression/ Double shear	35	35	80–160	CP
[106]	NC	Steel	EPS/XPS	GFRP truss	Eccentric compression/ Four-point bending	50–80	50–80	50–80	CP
[153]	SCC	Steel	EPS	Steel truss	Concentric compression	25	25	50–100	CP
[154]	NC	Steel	EPS	Steel tie bars	Concentric compression	50	50	85	CP
[112]	FC	Steel	EPS	Steel truss	Concentric compression	50	50	25	CP
[119,155]	NC	BRFP	EPS	BFRP bars	Combined axial-flexure/ Double shear	60	60	150	CP
[156]	UHPC	GFRP grid	XPS	GFRP bars	Combined axial-flexure	25	25	152	CP
[157]	SC	Steel	EPS	Steel tie bars	Cyclic in-plane lateral	35	35	80–130	CP
[158]	CC	Steel	Polystyrene board	Steel tie bars	In-plane lateral	75	75	50	CP
[159]	NC	Steel	XPS	Steel stirrups	Cyclic in-plane lateral	50	50	100	CP
[105,110, 111, 120]	GC	Steel/BFRP	XPS/Rockwool	GFRP hexagonal tubes/Thermomass CC-series	Four-point bending/ Concentric & eccentric compression/Fire	75–100	75–100	50–100	CP
[160]	NC	Steel	Mineral wool	GFRP bars	Fire	70	140	60–200	NCP
[161]	NC	Steel	EPS	Steel struts	Fire	50	50	50	CP
[162]	NC	Prestressing strands/Steel	EPS/XPS/PIR	Thermomass CC and NC series/carbon cast C-grid/steel C-clip	Blast	76.2	76.2–152	50.8	CP/ NCP
[163]	SC	Steel	EPS	Steel tie bars	Blast	50.8	50.8	50.8–101.6	CP
[164,165]	LWC	Steel	XPS	GFRP bars/Hybrid steel-GFRP bars	Double shear/Drop-weight impact	55–75	55–75	90	CP

Note: t_{ext}, t_{int}, and t_{ins} refer to the thickness of the external concrete wythe, internal concrete wythe, and insulation layer, respectively; NC–normal concrete, RAC–recycled aggregate concrete, SCC–self-consolidating/compacting concrete, LWC–lightweight concrete, TRC–textile reinforced concrete, HPFRC–high-performance fibre reinforced concrete, SC–sprayed concrete, FC–foamed concrete, UHPC–ultra-high performance concrete, CC–ceramsite concrete, GC–geopolymer concrete. CP–composite panel, NCP–non-composite panel. Refer to Table 4 for the acronyms of corresponding insulation.

Table 4
Insulation types with their corresponding acronyms.

Acronyms	Insulation types
EPS	Expanded Polystyrene
XPS	Extruded Polystyrene
PIR	Polyisocyanurate
PUR	Polyurethane
GFR-PUR	Glass Fibre Reinforced Polyurethane
EPS-FC	Expanded Polystyrene based Foamed Concrete
RW	Rockwool
FC	Foamed concrete
VIP	Vacuum Insulated Panel

composite action. It should be noted that the failure of the non-composite shear connectors in non-composite PCSPs may lead to the detachment of the concrete wythes without compromising the structural function of the buildings, as seen in Fig. 13(a). However, such failures could still be dangerous to the safety of the people around the buildings (especially in multi-storey buildings). On the other hand, failure of the composite shear connectors in composite PCSPs may directly affect the axial load-bearing capacity of the panels which may lead to the building collapse.

Realising the significance of composite shear connectors in maintaining the composite action and the several benefits of the composite PCSPs, many commercial composite shear connectors were developed and are being used in different parts of the world. Shear connectors can be made of concrete, steel, and FRP materials, as shown in Fig. 14, Fig. 15, and Fig. 16, respectively. Initially, concrete [101], steel tie bars/truss [112,152], and other metallic connectors [26,96,139] were used to connect the internal and external wythes. However, it was found that the use of concrete and steel to connect two concrete wythes could lead to thermal bridging and

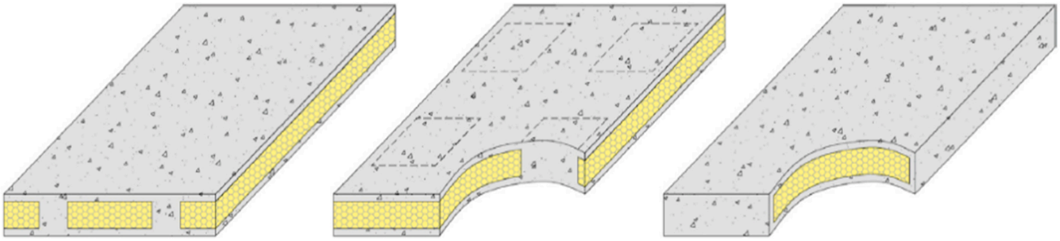


Fig. 14. Concrete grids as a shear connector [26].

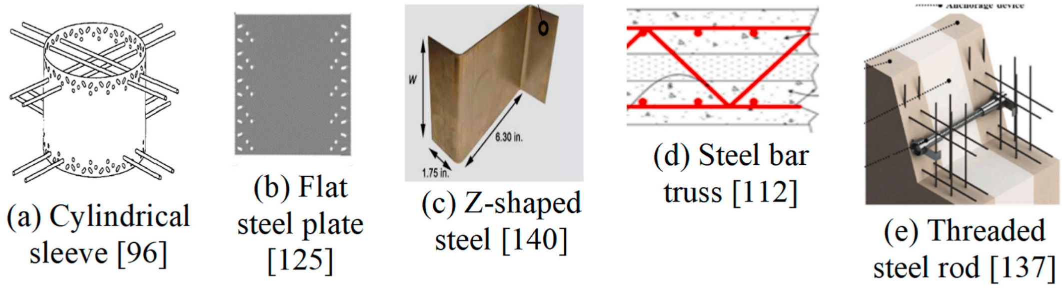


Fig. 15. Steel shear connectors.

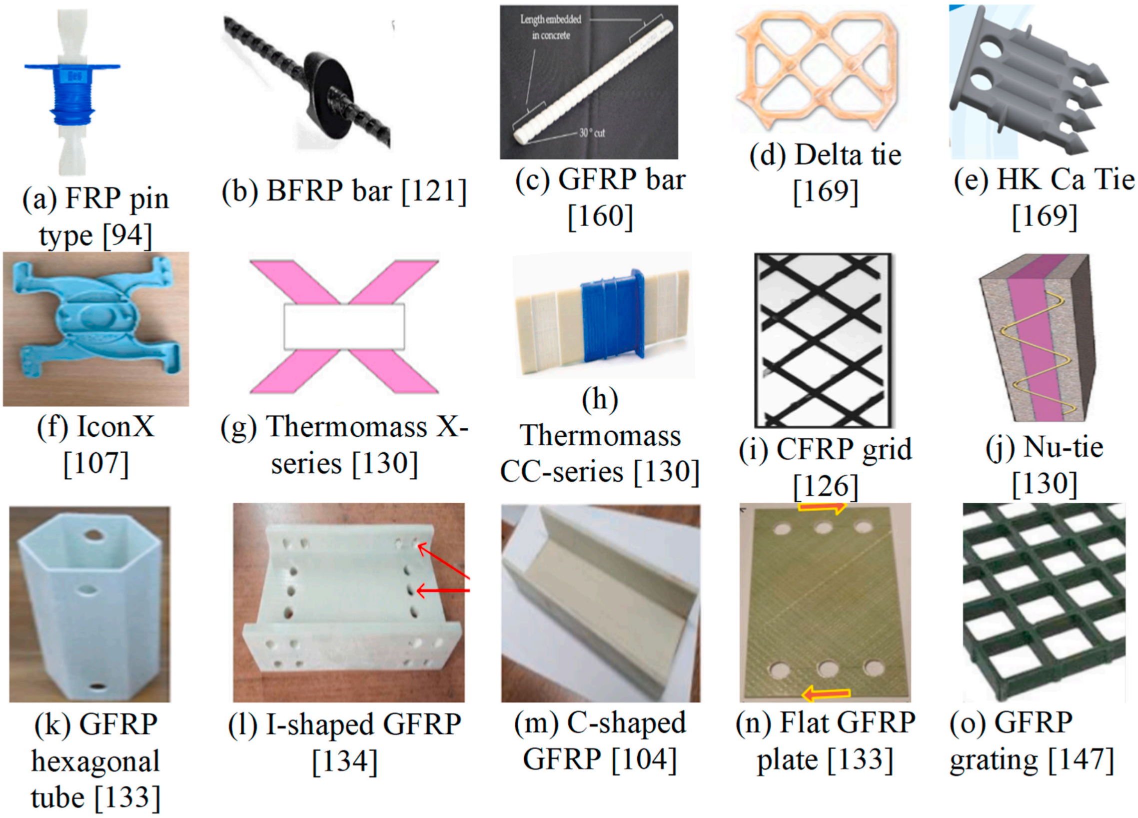


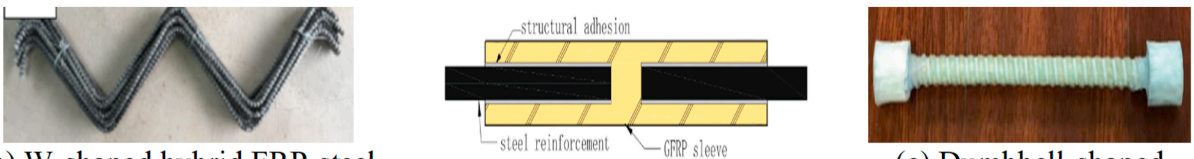
Fig. 16. FRP shear connectors.

reduce the thermal resistance of the panel by almost 41 % (with 0.1 % stainless steel connectors cross-sectional area to that of panel surface area) and 37 % (with 1.0 % concrete grids cross-sectional area to that of panel surface area), respectively [96]. Therefore, several FRP connectors were introduced, owing to the low thermal conductivity (nearly 1.7 % that of stainless steel and 14 % of concrete) characteristics [24], as depicted in Fig. 16.

FRP materials possess high tensile strength and weak shear capacity [131,132], which may lead to some level of reluctance in using FRP shear connectors in the sense that it may compromise structural safety. The effective shear resistance of FRP connectors can be significantly improved by adopting an inclined placement, engaging the high tensile resistance of the FRP through a truss mechanism [121,155]. Ref [155] can be referred to for a detailed explanation of the truss mechanism of the FRP shear connectors. A similar mechanism has been adopted in the design of most of the commercially available composite shear connectors shown in Fig. 16(d–j). Nonetheless, several connectors have their own limitations and proprietary design procedures. For instance, PCSPs with IconX connectors in Fig. 16(f) exhibited good composite action in flexure and compression [107], but these kinds of connectors can only be used in PCSPs with a maximum insulation thickness of 100 mm [168]. Likewise, steel truss connectors develop high composite action [136], but are suited to panels with insulation thickness greater than 100 mm [95]. In addition, continuous shear connectors like steel truss and CFRP grids create gaps in between the insulation, which needs to be filled in using spray foam having similar thermal properties to that of the insulation layer. This often becomes a challenge during fabrication, as concrete flows into voids in foam resulting in thermal bridges between the wythes [96,136,150]. Another limitation is the orientation of the shear connectors. The majority of the existing shear connectors are one-way shear connectors and resist shear effectively in the longitudinal or in-plane direction, while in the transverse or out-of-plane direction (Fig. 18), these connectors may exhibit poor shear resistance [125,168]. This necessitates strict fabrication control on the alignment of the one-way shear connectors. On the other hand, two-way shear connectors like cylindrical steel sleeves in Fig. 15(a) offer flexible fabrication and uniform shear resistance in all directions. However, their applicability in composite PCSPs has not been explored, which might be due to an increase in thermal bridging using many numbers of steel sleeves. Apart from the above-mentioned limitations, design engineers have to rely on the design information and shear capacity of the commercial connectors provided by the manufacturer [95,122], as there is no appropriate guideline on the selection and strength prediction of those connectors. The availability and cost of the commercial shear connectors also play a deciding factor in the selection of the connectors.

Nevertheless, researchers have developed and investigated many types of FRP shear connectors to improve the composite action, reduce thermal bridging, and make fabrication easier. Recently, Huang et al. [133] developed two-way GFRP hexagonal tube shear (as shown in Fig. 16(k)) connectors along with an anchorage system, which exhibited significantly higher shear strength (almost uniform in both in-plane and out-of-plane directions), stiffness, and composite action than the commercially available Thermomass CC-series connectors (Fig. 16(h)) [105]. However, due to the thin wall of the hexagonal tubes, many numbers of connectors were required in the flexural test specimens to achieve a high degree of composite action, which might create fabrication difficulty for the insulation layer in practical applications. While increasing the thickness of the hexagonal tube will, undoubtedly, increase the shear strength and stiffness, it cannot be stated at this stage whether it would be an optimised section (compared to circular or square tube sections). Furthermore, the shear performance of the hexagonal tubes was investigated considering only 50 mm thick insulation, and it might provide lower shear resistance with a thicker insulation layer (i.e., 100 mm–300 mm, which is not uncommon to meet the thermal performance requirements in harsh climates). More recently, Pan et al. [104] and He et al. [134] proposed I-shaped (Fig. 16 (l)) and C-shaped (Fig. 16(m)) GFRP shear connectors, respectively, for non-composite type PCSPs with a thicker insulation layer up to 300 mm. In terms of shear strength and stiffness, the I-shaped connectors outperformed the hexagonal tube connectors. Overall, the existing research on the development of two-way FRP shear connectors and composite PCSPs is limited, and a lack of knowledge on the overall structural performance of PCSPs under static and dynamic loadings might prevent their wide application in the construction industry. Recently, a significant step was undertaken by the Tilt-Up Concrete Association to promote the wide application of composite PCSPs by investigating their structural performance under flexural and combined axial-bending loads and proposed design methods for composite PCSPs using a variety of proprietary shear connectors, which might be used in the building code format in the future with the inclusion of more detailed design procedures and examples [169].

There is also a growing interest in recent years towards the development of FRP-steel composite shear connectors for PCSPs, as such hybrid FRP-steel connectors combine the benefits of the high shear strength of steel and the low thermal conductivity of FRP. Jiang et al. [131,132] studied the shear performance of W-shaped steel-GFRP (SGFRP) shear connectors (in Fig. 17(a)) and the flexural behaviour of composite PCSPs using W-shaped SGFRP connectors. The results from the shear tests exhibited higher shear strength of the SGFRP connectors compared to that of only GFRP or steel [131]. However, bending tests on panels revealed debonding of the concrete wythes due to a lack of proper anchorage [132]. Wang et al. [138] developed FRP-jacketed steel-composite shear connectors, as shown in Fig. 17 (c), and investigated the bending resistance of the non-composite type PCSPs with a large insulation layer thickness of 130 mm. Similarly, Yang et al. [164] used hybrid GFRP-steel (Fig. 17(b)) connectors to investigate the impact resistance of the composite PCSPs exhibiting excellent bonding between the concrete wythes. However, the fabrication of PCSPs with hybrid



(a) W-shaped hybrid FRP-steel [131]

(b) Hybrid FRP-steel tie bar [164]

(c) Dumbbell-shaped hybrid FRP-steel bar [138]

Fig. 17. Hybrid FRP-steel shear connectors.

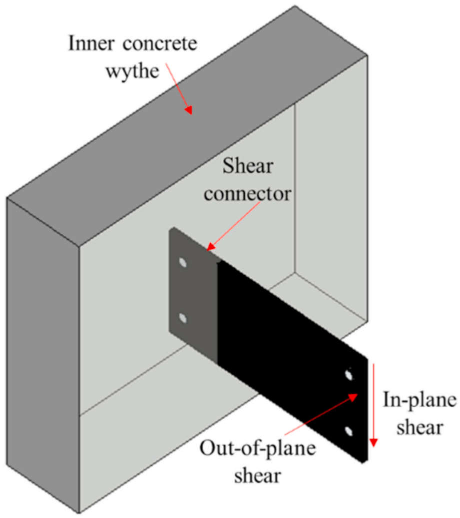


Fig. 18. Shear force acting on one-way connector (Insulation and outer concrete wythe are omitted for clarity).

GFRP-steel connectors in Ref. [164] might be time-consuming as both ends of a large number of connectors need to be welded to the reinforcement layers of the concrete wythes. Hence, future research works focusing on the development of cost-effective and robust two-way shear connectors made up of FRP or hybrid steel-FRP material for composite PCSPs could be beneficial.

2.5.3. Insulation layer in PCSP

Since the purpose of developing PCSP was to address the shortcomings of the solid precast concrete panels towards better thermal insulation, light weight and energy efficiency of the buildings [170,171], researchers have utilised various insulating materials as core of the PCSPs to achieve high thermal insulation performance. Although the main function of the insulation foam layer is to provide thermal resistance, it offers a certain level of shear resistance between the concrete and insulation layer [155]. However, the failure of such shear bonding is unpredictable and not considered in the design of PCSPs. For that reason, investigation on the shear resistance of the connectors in PCSPs is often carried out by applying a plastic sheet as a bond breaker in between the concrete and insulation to obtain the realistic shear capacity of the connectors [123]. Some of the commonly adopted insulating materials in PCSPs include PUR, EPS, and XPS foams [25], as illustrated in Table 3. Other insulation materials include glasswool, rockwool, and vacuum insulated panels (VIP) [95]. VIP insulation has the lowest thermal conductivity of 0.004–0.008 W/mK compared to that of XPS (0.030–0.037 W/mK), EPS (0.030–0.040 W/mK) and PUR (0.023–0.027 W/mK) [95]. VIP insulation was used to develop thin PCSPs with high thermal resistance, indicating VIP insulation as an efficient insulating layer [150]. However, VIP insulation is costly and fragile and requires careful handling to avoid compromising the internal vacuum [95]. As a non-combustible material, rockwool and glasswool insulations were used in panels during fire tests, demonstrating the application of such insulation materials where high fire resistance is desired [120,160]. The selection of insulation materials often depends on the thickness of the insulation layer (20 mm–300 mm in Table 3), cost, thermal resistance (R-value), size, and availability. For example, to achieve a higher R-value, VIP insulation with low thickness can be used, but the cost of the panel will increase significantly. Similarly, the thickness of the insulation layer with PUR foam would be less compared to EPS and XPS foams to achieve the same R-value [172], while it would also incur a higher cost. There are several other insulation materials available commercially. Airium, for example, is a non-combustible mineral foam made of cement-based slurry, aqueous foam, and air bubbles. It possesses thermal conductivity as low as 0.035 W/mK, similar to that of EPS/XPS foams [173], and might develop better bonding with the concrete wythes than other insulating foams. As a result, it could potentially be used as an insulation layer in future studies of PCSPs. Ref [174] can be referred to for more information on building insulation materials. Table 4 illustrates the different types of insulation materials considered in the studies of PCSPs.

3. Structural performance of PCSPs

Wall panels are subjected to various loading scenarios during their service life in any building structure. Hence, they are designed accordingly to be able to withstand those loads. Load-bearing walls are designed to resist axial (both concentric and eccentric) loads from the floors and upper-storey walls, flexural loads from wind pressure, fire, and seismic loads. Non-load-bearing walls are designed to sustain wind pressure in flexure, racking loads, and fire. Sometimes, both load-bearing and non-load-bearing wall panels are designed to resist impact and blast loads. The adequate strength of connections among wall panels, floors, and frames must be ensured to maintain the structural integrity, serviceability, and robustness of the buildings. Several research studies have been carried out in the past to investigate the structural behaviour of a variety of PCSPs and their shear connectors under various load conditions. A few works were also reported on panel-to-panel and panel-to-frame connections, which will be discussed in the following sub-sections.

3.1. Shear tests on connectors

As discussed in section 2.5.2, shear connectors are the important components of the PCSPs, particularly for composite PCSPs. Unlike steel-concrete-steel sandwich panels, the shear behaviour of the connectors in PCSPs is complex due to flexible foam insulation in between the concrete wythes that do not provide restraints to the connectors to resist shear. As a result, shear connectors are subjected to combined shear and bending. Therefore, before the selection of any shear connectors for the design of PCSPs, the shear behaviour and strength properties of the connectors must be known. At present, there is no widely accepted standard test method for testing the shear performance of the shear connectors in PCSPs [122,169]. However, two test methods recommended by the International Code Council-Evaluation Service (ICC-ES) (i.e., AC320-single-shear test [128] and AC422-double-shear test [169] methods) have been popularly used by researchers in the past. In a comparison study of these two testing methods, the AC422 method was found to provide a more accurate measure of the strength properties of the connectors with a large variability among the tested specimens [122]. Also, in Table 3, it can be noticed that many studies were carried out to study the shear-resistance of the several proposed shear connectors (steel, FRP, and hybrid steel-FRP), where the majority of them adopted double-shear test methods. However, further research into the shear tests of connectors with varying testing parameters and/or methods was recommended by Parker et al. [122] to decrease the variability among the test results produced from the double shear test method.

More recently, anchorage system design of shear connectors using steel anchor bars was proposed [104,134], as discussed in section 2.5.2. External wythes are exposed to the open environment and steel reinforcement in concrete wythes is susceptible to corrosion. The anchor bars of shear connectors are embedded into the concrete wythes and are not visible for visual inspection and maintenance. Deterioration of steel anchor bars from corrosion may compromise the integrity of the PCSPs, especially the composite PCSPs. Further research by incorporating the corrosion-resistant FRP anchor bars could be explored to study the failure mechanism and pull-out capacity of the shear connectors.

3.2. Flexural tests on PCSPs

For an external wall, either load-bearing or non-load-bearing, the ability to resist flexural load generated from the wind pressure or due to eccentric compression [57] is an essential criterion to meet the design requirements for strength and serviceability. As per the serviceability limit state criteria suggested by AS/NZS 1170.0:2002, the mid-span deflection should not exceed span/150, span/250, and span/500, for face-loaded general wall elements to control the discerned movement, façade damage, and cracking of brittle cladding, respectively [175]. Many studies have been conducted to investigate the flexural performance of PCSPs using various types of concrete, reinforcement, shear connectors, and insulation, as outlined in Table 3. Due to the lack of standardised test methods for flexural tests on PCSPs, various flexural test methods have been employed in the past, including the quasi-static three-point bending test [150], four-point bending test [107,113,114,139,149], six-point bending test [56,129], uniformly distributed pressure using water bladder apparatus test [146], and sixteen-point bending tests [162]. Few studies also examined the performance of PCSPs under cyclic loading [136,141] to understand the cyclic flexural behaviour, when used as non-load-bearing external walls in buildings in cyclonic regions. It is worth noting that the majority of the existing research on the flexural behaviour of PCSPs (in Table 3) has used steel-reinforced concrete wythes. In precast concrete claddings, as discussed in section 2.5.1, corrosion of steel reinforcement due to the exposed environment often reduces durability and increases maintenance costs [118]. The moisture ingress in outer concrete wythes due to wetting and drying cycles may corrode external steel reinforcement and lead to corrosion of steel shear connectors [118], which could affect the structural integrity of PCSPs. Hence, research on the moisture penetration resistance of the PCSPs with steel as well as FRP connectors could be one future research to provide more confidence in using composite PCSPs as a structural component. FRP reinforcement in RC elements has been widely investigated in the past due to its high strength, lightweight, sustainability, and corrosion-resistant properties. Some researchers focused on investigating the flexural resistance of the BFRP-reinforced PCSPs [105,119], which exhibited excellent potential application of BFRP rebars in PCSPs. However, more research into the flexural performance of BFRP-reinforced PCSPs using a variety of shear connectors would be relevant for developing proper design methods and providing confidence to the industry for practical application.

3.3. Compression tests on PCSPs

Load bearing walls are designed to carry vertical/compression load from the floor and wall of the upper storey. The compression load may be concentric [111] or eccentric [110], depending on the design, and the performance of the sandwich panel relies on the axial compressive strength of the panel as well as its composite action. From Table 3 and it can be observed that limited research has been carried out to explore the axial compression performance of the PCSPs. This could be due to several reasons. Firstly, the majority of studies investigated the performance of non-load-bearing PCSP walls, where compressive load-bearing capacity was irrelevant. Secondly, traditional industry practice was to use non-composite PCSPs as a load-bearing wall (as shown in Fig. 8 (a)) in which the inner wythe is the structural wythe designed in a manner similar to a solid precast concrete wall. However, composite PCSP walls with thin concrete wythes are complex and different from non-composite PCSPs, and inadequate composite action from the shear connectors will affect the axial load-bearing capacity of the walls.

A few works were carried out to evaluate the compressive load-bearing capacity of composite PCSPs [106,107,112,151], as listed in Table 3. As a result, there is a growing interest in studying the performance of axially loaded composite PCSPs. Kumar et al. [110,111] explored the concentric and eccentric compression resistance of the sustainable BFRP-reinforced precast geopolymer concrete sandwich panels with hexagonal GFRP tube shear connectors. The experimental results revealed excellent load-bearing capacity and potential for application in multi-storey prefabricated buildings. Both ends of the walls were prefabricated using end capping beams [110,111], as shown in Fig. 19(a), which is different from the common industry practice where continuity in the insulation

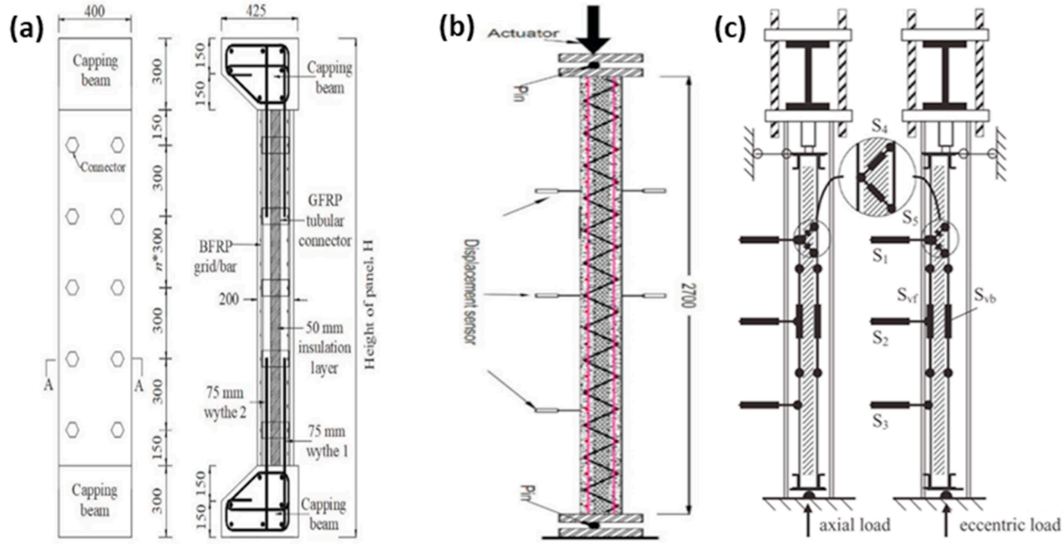


Fig. 19. Compression test specimens designed (a) with end-capping beams [110], (b) without end beams [106], and (c) with solid concrete ends [152].

layer is preferred (refer to Fig. 8). Also, there is a variation in the fabrication of the test specimens with different end conditions for compression tests in the literature, as depicted in Fig. 19. The results and compressive behaviour of the composite PCSPs might not be consistent due to varying end condition, which is still unknown. Therefore, to promote the wide application of composite PCSPs as load-bearing walls, more detailed research on the axial load-bearing performance of the composite PCSPs would be needed considering the end condition of the panels according to the industry practice and employing more robust shear connectors and FRP reinforcement in concrete wythes. Additionally, for architectural purposes, it is not uncommon to design external wall panels with a curved shape. The curved solid RC panel is often used in practice, which is fabricated by modifying the formwork. However, the compressive behaviour of curved PCSPs and shear connectors connecting two wythes might be more complex than the straight panels, which remains unknown at present and would be worthy of investigation, as it could promote flexibility in architectural planning and design of the buildings.

3.4. Impact tests on PCSPs

External walls could sometimes suffer from impact due to windborne debris, flying debris in the event of a blast, and vehicle impact, which could severely damage the building envelope, compromising the performance of the buildings and the safety of the occupants. Hence, the resistance of external wall panels to impact is of concern, especially for important buildings and cyclonic regions. For example, AS/NZS 1170.2:2021 may require that walls are able to resist impact by a 4 kg timber projectile, with a nominal cross-section of 100 mm × 50 mm at impacting end, at an impact velocity of 0.4 V_R (where V_R is the regional design wind speed), normal to the wall surface [176]. Compared to other prefabricated wall panels, PCSPs could offer excellent resistance to windborne debris impact during hurricanes and tornadoes, providing safety to the occupants [164]. Moreover, when used as load-bearing walls in multi-storey buildings, the impact from accidental actions like vehicle impact should be considered to prevent the progressive collapse of the buildings, as specified in the standards such as European Standard, EN 1991-1-7 [177], WorkSafe Victoria [178], and Australian Building Codes [179]. Besides walls, PCSPs can be applicable to roof and slabs [116,180], which might be subjected to impact loading. Nevertheless, the study on the impact resistance of PCSPs is very limited. Recently, Yanmin et al. [164] studied the drop-weight impact performance of the precast lightweight concrete sandwich panels using hybrid steel-FRP shear connectors, which showed excellent impact resistance. In addition, a few recent research works presented the performance of the RC wall panels subjected to impact loading [181–183]. However, to the best of the author's knowledge, the study on the impact resistance of axially-loaded PCSPs does not exist in the literature at present. Hence, it is recommended to investigate the dynamic performance of the load-bearing composite PCSPs subjected to impact loading, which could be beneficial in designing safe buildings.

3.5. Blast tests on PCSPs

Due to rising explosion events around the world, either accidental or intentional, there is increased interest among structural engineers and researchers to design resilient structures by developing energy-absorbing cladding systems. Building envelopes should possess enough strength to resist blast loads to a certain extent and prevent the collapse of structures (especially in panelised building systems) and safeguard the life of the residents. The blast resistance of PCSPs has been evaluated by a few researchers, as evident from the literature [162,163,184,185]. However, the existing studies on the blast performance of PCSPs were based on limited types of commercially available shear connectors and concrete wythes reinforced with prestressing strands and steel rebars. A study on PCSPs with steel connectors subjected to blast load revealed that PCSPs have lower blast resistance compared to precast RC panels [184]. While the study on the blast performance of load-bearing solid precast concrete panels was carried out in the literature [186], there is no research on the behaviour of load-bearing composite PCSPs at present. Also, the recommended values of the displacement and support rotation for the design of non-load-bearing PCSPs under blast loading are presented in Ref. [187]. However, there is no such guide on the blast-resistant design of load-bearing composite PCSPs, which is deemed as future research work.

3.6. Racking tests on PCSPs

In general, walls are subjected to in-plane lateral load (racking force) during earthquakes and provide lateral stiffness to the building itself (as structural load-bearing or shear walls) or to the frame of the building (as infill walls). In panelised construction, as shown in Fig. 2(b) and Fig. 20, several prefabricated wall and floor panels are interconnected along the length and height of the buildings. While in volumetric (Fig. 2(a)) and framed prefab (Fig. 2(c)) construction, wall panels are connected to steel and precast concrete frames as infill walls or cladding. Hence, the connections between them are crucial in maintaining structural integrity and preventing the detachment of the walls from the frame. Several works have reported on the seismic behaviour of the PCSPs, as listed in Table 3. In a study conducted by Ma et al. [158], PCSPs with ceramsite concrete exhibited excellent performance in hysteresis, ductility, and seismic energy consumption. Lu et al. [159] studied the response of L-shaped PCSP under seismic loading and showed desirable seismic performance. The results from the lateral load tests on PCSPs with and without openings also exhibited good performance [157]. Recently, He et al. [180] carried out a seismic test on a two-storey full-scale building with PCSPs, which revealed the excellent potential of PCSPs for application in a multi-storey building. To use PCSPs as infill walls in steel and concrete framed buildings, researchers investigated the lateral in-plane shear performance of the concrete-filled steel tube (CFST) frame [188] and RC frame [189] infilled with PCSP. Nevertheless, steel shear connectors were commonly adopted in the existing studies related to the lateral in-plane shear behaviour of the PCSPs. Therefore, future studies on the lateral in-plane shear resistance of composite PCSPs (with/and without openings) with FRP shear connectors and FRP reinforcement could provide more information on their seismic performance and design for practical application.

3.7. Fire tests on PCSPs

Fire performance of the prefabricated wall panels (especially in panelised construction) is another challenge, as there is a high risk of fire damage causing a reduction in the load-bearing capacity of structural walls. There have been several fire accidents in building structures, such as a fire in a high-rise building in Changsha, China, where combustible building facades were considered the main reason for the rapid fire spread [190]. Therefore, wall panels could play a vital role in the fire performance of the prefab building by preventing the spread of fire. Moreover, the standards and codes have become stricter regarding the fire resistance level (FRL) of the building materials and components. In Australia, as per the NCC [71], the minimum FRL of external load-bearing walls is 90/60/30 min in terms of structural adequacy/integrity/insulation and goes high up to 240/240/240 min depending on the building class and construction. Also, the components of the external walls in buildings of three-storey or more must be non-combustible [71]. PCSPs could provide superior fire-resistant construction compared to other types of prefabricated wall panels, as PCSPs consist of inner and outer concrete wythes, making them inherently fire-resistant [95]. Also, the need for additional fire protection in PCSP is reduced due to its inorganic composition [95]. In a study by Huang et al. [120], PCSPs with BFRP-reinforced geopolymer concrete wythes, GFRP shear connectors and rockwool insulation, exposed to one side fire exhibited excellent fire resistance in a 4-h fire test. Also, Kontoleon et al. [161] revealed the good fire resistance behaviour of PCSPs with an additional external insulation layer, which needs to be carefully considered due to the prohibition of combustible materials in external walls of Type A (i.e., three-storey Class 2, 3, 9 and four or more storey Class 2, 3, 5, 6, 7, 8, 9 buildings) and Type B (i.e., two-storey Class 2, 3, 9 and three storey Class 5, 6, 7, 8 buildings) construction in Australia [71]. The current knowledge on fire resistance of load-bearing composite PCSPs is limited [120,191] and may require further full-scale fire tests to determine their strength and performance under fire.

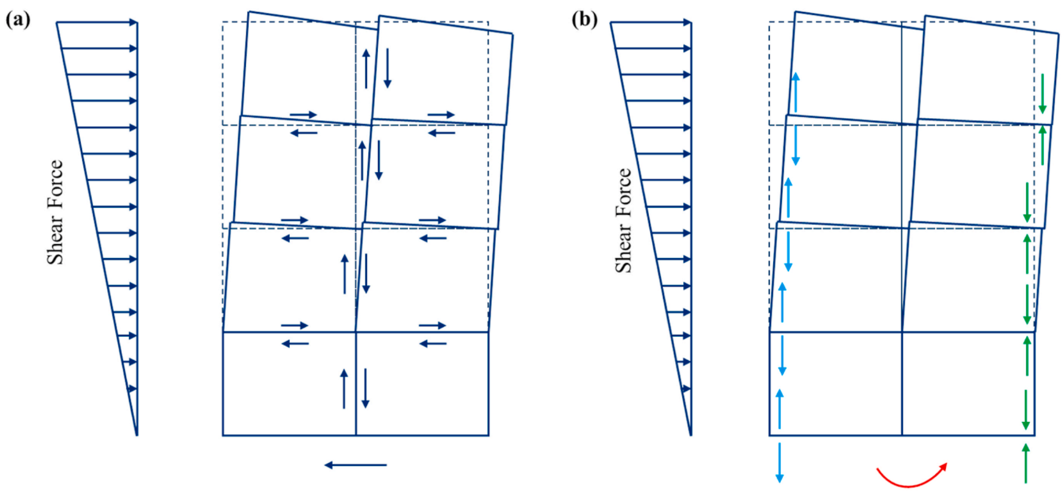


Fig. 20. Prefabricated wall panels subjected to in-plane action (a) shear forces, (b) tensile and compressive forces (based on [19]).

The composite PCSPs with high levels of thermal performance require insulation thicknesses greater than 100 mm, whereas the non-load bearing composite PCSPs require thinner inner and outer concrete wythes to reduce mass and material consumption. This change in the thickness balance requires additional consideration and testing for fire and seismic loads of thin-shell composite PCSPs to ensure that the exterior walls with combustible insulation must not contribute to the spread of fire, and the outer concrete wythe should not fall off the building, putting the firefighter at risk. Hence, non-load-bearing composite PCSPs require further testing and modelling to develop appropriate standards, as there is limited knowledge about the fire performance of non-load-bearing light-weight composite PCSPs in the current literature. Moreover, buildings with composite PCSPs would typically have vertical joints at floor level and horizontal joints at every 1 m to 3 m, which needs to be investigated for fire resistance.

4. Connections for PCSPs

In prefabricated construction, connections of the buildings are important. The in-plane action of the prefabricated walls is crucial to maintain the structural integrity where the interacting prefabricated wall panels are designed to act as one structural unit, which is secured by the structural connections to resist required shear, tensile and compressive forces, as shown in Fig. 20. Although design guidelines on the connections of non-composite PCSPs are available [102,192], limited research works have been carried out on the connection among composite PCSPs as well as the overall structural performance of the panelised building system utilising load-bearing composite PCSPs [180], which is crucial for maintaining the structural integrity of the building similar to the precast concrete volumetric construction [193]. PCSPs are widely used in panelised building systems as load-bearing walls that are connected to transfer and resist structural loads. Failure of such connections could compromise the robustness of the structure and may result in the collapse of the buildings. The main reason behind limited research on the connections among PCSPs may be due to the wide application of the non-composite PCSPs in which the inner concrete wythe (structural wythe) is thick like solid precast concrete panels, and their connection system is similar to normal precast panel connections, as shown in Fig. 21. As depicted in Fig. 21, all the connecting components are installed within the inner wythe, while the outer concrete wythe just acts like a cantilever transferring its self-weight to the inner wythe through shear connectors and does not require connection with the floor and surrounding walls (upper and lower), as shown in Fig. 8(a). However, this may not be the case when using composite PCSPs (which is gaining popularity in recent years) as load-bearing walls supporting the wall and floor above, where both the concrete wythes are thinner (often 50–75 mm) and carry the structural load together, as shown in Fig. 22. The connection between such wall panels must be robust enough considering both the wythes of the composite PCSPs. Recently, a bolt connection system (in Fig. 22) for composite PCSP walls and floors was proposed, and a shake table test was performed on a two-storey full-scale building [180]. The test results exhibited high lateral stiffness and strength as well as ductility in resisting earthquakes [180]. However, the proposed system might be challenging for multi-storey buildings, as it requires the installation of a large number of bolts on the outer surface. Hence, the design of a connection system that can be installed from the inside of the wall panels (similar to the connection of traditional precast concrete panels) to connect both wythes during construction would be significant, and future research may aim towards achieving such innovative designs.

The prefabricated wall panels also enhance the lateral stiffness of the volumetric steel frames to resist seismic and wind loadings [194]. In such a loading scenario, the wall panels and their connections with the frame must be able to withstand the in-plane and out-of-plane forces. Otherwise, it may lead to the detachment or collapse of the wall from the main structural frame [195]. With the growing interest in the application of PCSPs as external facades, Wang et al. [188] investigated the seismic behaviour of the blind bolted concrete-filled steel tube (CFST) frames infilled with composite PCSPs, as shown in Fig. 23(a), where the panels were connected to the frame using bolts and steel plates. The experimental outcomes revealed good seismic resistant performance, and the structural integrity of the PCSP with CFST frame was maintained. Thus, the bolted connection was suggested as a reliable method to connect PCSPs with CFST frames. Recently, retrofitting the RC frame with external PCSPs (by replacing masonry infill) was proposed,

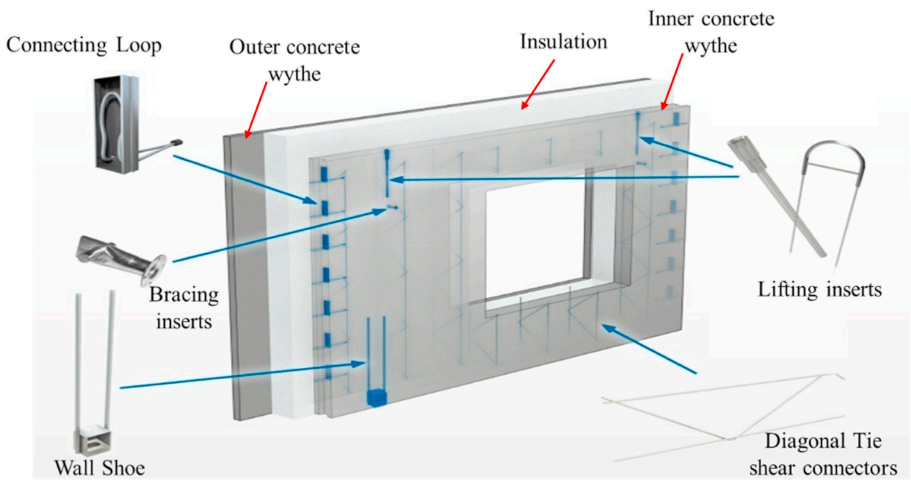


Fig. 21. A typical non-composite PCSP with various connecting components [196].

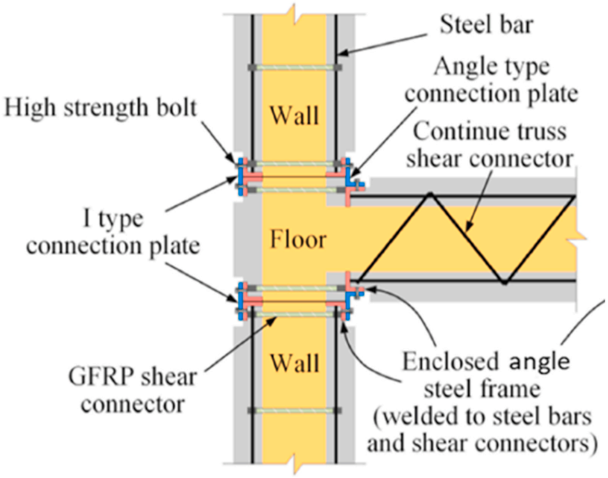


Fig. 22. Bolt connection system for composite PCSP walls and floor panels [180].

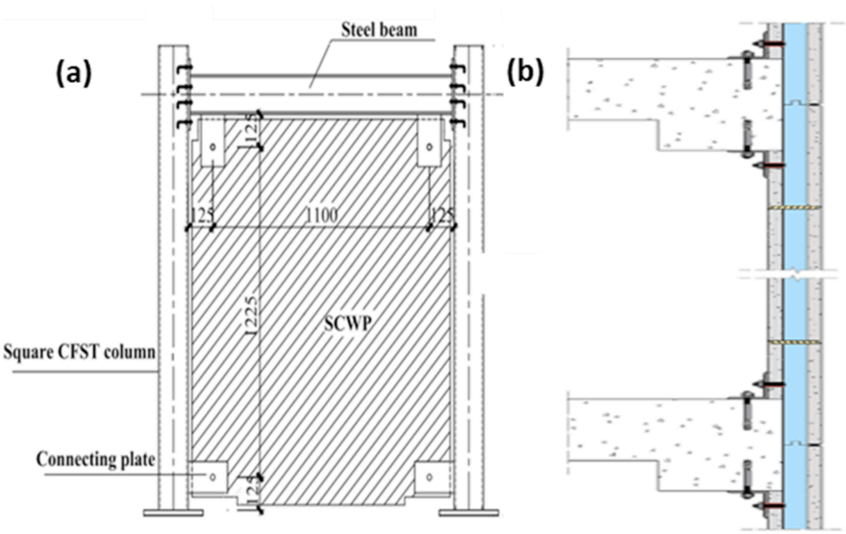


Fig. 23. (a) PCSP connected to CFST using steel plate and bolts [188], (b) PCSP connected to RC frame using angle plates and bolts [189].

as depicted in Fig. 23(b), and the lateral in-plane cyclic loading test was performed on the RC frames with PCSPs connected using angle steel plates and bolts [189]. The test results demonstrated excellent lateral strength and energy dissipation of RC frame with PCSPs compared to masonry infills. The existing studies on connection systems among PCSPs as well as panels-to-frames (steel and concrete) provide relevant information but to a limited extent. More robust and easier-to-assemble connection methods for the composite PCSPs could be a topic for future research. Research on the overall behaviour of the building constructed using composite PCSP system and their connections could be very useful for the design engineers.

5. Thermal performance of PCSPs

In addition to the structural performance, the PCSP acts as the environmental separation element, providing heat, air, and moisture (HAM) management [197]. For energy-efficient and sustainable prefab buildings, the building envelope plays a crucial role by delivering thermal comfort in an indoor environment. The building codes have introduced stringent provisions regarding the thermal performance requirements of the external wall panels to reduce the heating and cooling energy consumption to meet the net-zero target in the future. In Australia, as per the NCC [71], exterior walls must achieve a total thermal resistance (R-Value) of 2.8 m^2.K/W (2.4 m2.K/W with shadings in climate zones 1, 2, 3, 4, and 5) in climate zones 1–7, and 3.8 m^2.K/W in zone 8. A recent review article [94] highlights that PCSPs have R-Values ranging from 0.23 to 10 m^2.K/W depending on the insulation type and thickness. This makes them suitable for use as energy-efficient building façade to achieve net-zero housing by selecting the appropriate R-value based on the specific requirements. Furthermore, PCSPs as a building envelope offer higher performance in air and moisture management compared to other facades constructed of multi-component layer [198]. Also, PCSPs as external walls have already been proven to contribute to net-zero buildings by reducing the heating and cooling energy requirements of the buildings significantly [199]. Woltman et al. [200] investigated the thermal properties of PCSPs with GFRP and steel connectors experimentally and numerically. They demonstrated that the PCSP with GFRP connectors has an R-Value between 2.84 and 4.68 m^2.K/W, higher than that of 2.74 m^2.K/W with steel connectors. In a demonstration building, PCSPs with VIP insulation, FRP connectors and HPFRC achieved an R-Value of more than 5.55 m^2.K/W [150]. In Ref. [201], the thermal performance of PCSPs with steel connectors was investigated, revealing that such PCSPs can achieve an R-Value of 1.82 m^2.K/W. Table 5 presents the thermal resistance performance of PCSPs with various insulation material, thickness of insulation and connector types, observed from the tests in the literature. More recently, the development of hybrid steel-FRP shear connectors, as discussed in section 2.5.2, has emerged to improve the shear resistance and composite action in PCSPs. The experimental investigations on the thermal conductivity of such hybrid connectors in PCSPs could be beneficial and relevant for practical applications.

The joints between PCSPs are also critical for HAM management [202]. The rainwater and moisture penetration through joints may reduce the efficient performance of the PCSPs [203]. There is a well-developed body of knowledge about the HAM management of heavy-weight non-composite PCSPs [102]. However, with the development of lightweight composite PCSPs, research related to the HAM performance of such panels is currently not well developed. The lightweight composite PCSPs may be highly efficient as a building envelope, but it may be vulnerable to joint failure in the event of earthquake and fire. Future research could explore the joint design of thin composite PCSPs considering fire and seismic scenarios and ensure that HAM requirements can be achieved.

6. Theoretical and FE modelling

At present, there are no appropriate design guidelines for the design of composite PCSPs [107,108,169,206], and the design of such panels can only be performed by tests or experience (i.e., the effective moment of inertia is determined from the tests or experience) [102]. Similar to the method suggested for calculating the shear capacities of steel connectors and concrete solid zones in PCSP [207], guidelines on the design and selection of suitable FRP shear connectors for composite PCSPs would be more beneficial for design engineers for the practical design of composite PCSPs. The existing connector-system-specific design of PCSPs using commercial proprietary shear connectors is often provided by the manufacturer of the shear connectors. The design of PCSPs is mainly based on simplified analytical models that consider either full or non-composite action [106,206] and are published in the form of some design examples in Precast Concrete Institute (PCI) publications [192,207,208] and Canadian Precast Concrete Institute (CPCI) design manual [102], along with the building codes used for traditional solid RC wall panels. This leads to overestimated (for full-composite assumption) and underestimated (for non-composite assumption) strength and does not reflect the actual performance of the PCSPs. Additionally, many researchers have proposed theoretical models to predict the responses of a variety of PCSPs in compression [110–112,151,153,154,209], flexure [116,145,210], in-plane lateral load [159], fire [191], and blast [162,211], as well as the shear capacity of the connectors [104,134,140,155]. Recently, Maguire and Rubaye [169] discussed and compared various design and analysis methods used for PCSPs and proposed a horizontal shear design. Also, the methods to analyse the cracking and ultimate moment considering the shear deformation produced due to slip between the concrete wythes were presented [169].

Compared to experimental studies, owing to the materials, cost, and time-saving benefits, Finite Element (FE) modelling is commonly employed to investigate the behaviour of structural components in a detailed manner. Moreover, properly validated FE models may provide more realistic behaviour of the components compared to simplified analytical methods with several assumptions. In the past, researchers have developed FE models to predict the shear behaviour of the shear connectors in PCSPs [124–126,133,134], as well as the structural performance of PCSPs under various types of loadings, including flexural [105,107,108,144,148,212], compression [106,107,112,151,152,154,213], combined axial-bending [208], fire [120,161], in-plane lateral load [188], impact [164] and blast loadings [184,185]. The commonly used commercial FE modelling software in the literature included ABAQUS [108,151,154,185], ANSYS [107,120], LS-DYNA [164,184], DIANA [114,126], and COMSOL [161]. The existing numerical models established were limited to the investigation of the performance of single panels. Future research works on employing validated FE models to study the horizontal and vertical connections among PCSPs and investigating the overall performance of the building system using PCSPs, as presented in Ref. [180], would be promising. Moreover, establishing FE models to study the performance of PCSPs and their connections with the steel and concrete frames for a proper understanding of their contribution to the lateral stiffness of prefabricated buildings would be essential in designing PCSPs as infill walls. In addition, FE investigations on the effects of openings on the structural performance of composite PCSPs could be useful.

Table 5
Summary of thermal performance of PCSPs.

Ref	Insulation type	Panel thickness (mm)	Insulation thickness (mm)	Connector type	R-Value (m^2.K/W)
[150,204]	VIP + Phenolic foam	150–170	40 + 50	CFRP grids	1.82–10
[201]	EPS	200	100	Steel bars	1.82
[200]	XPS	250	150	Steel bars	2.6–2.95
[200]	XPS	250	150	GFRP bars	2.64–4.96
[205]	XPS	250–310	30–90	Steel bars	1.25–3.05
[205]	XPS	280	60	GFRP bars	2.37

7. Concluding remarks and future prospects

Prefabricated wall panels as building envelopes are an important component of prefab buildings that contribute substantially to the overall energy efficiency of the building and provide safety for the building occupants. There are a few review studies carried out in recent years regarding the environmental, thermal, and structural performance of PCSPs suitable for claddings. However, several types of prefabricated wall panels exist in the construction industry with advantages and limitations, and there is a lack of a systematic review that presents the overall picture of the widely used prefabricated wall panels in the currently growing prefab industry. Therefore, a variety of prefabricated wall panels, including LTF, LSF, SIP, CLT, and PCSP panels, have been reviewed in this study with regard to their function, structural, thermal and fire performances, with an emphasis on PCSP and its components and their structural behaviour. The following concluding remarks are drawn from this review study.

1. Although the SIP is highly energy-efficient and lightweight, its application is limited to low-rise prefabricated buildings due to its low fire resistance and durability issues. Likewise, LTF and CLT panels are sustainable and are made from renewable resources, but the durability and fire resistance of timber materials pose limitations on their wide application. For mid-rise and high-rise buildings, LSF and PCSPs are often considered. When selecting prefabricated external walls, PCSPs could be preferred considering their durability, fire resistance, load-bearing capacity, and impact loading resistance.
2. PCSPs also offer higher thermal efficiency compared to many other wall panels, which helps in reducing energy demands and carbon emissions to achieve a high energy star rating for the buildings. As a result, PCSPs have been increasingly used as load-bearing and non-load-bearing walls in prefabricated buildings ranging from low-rise to high-rise.
3. The use of composite PCSPs is limited compared to non-composite PCSPs, and this has reduced the utilisation of the full benefits of the PCSP system in terms of materials and cost. The major reason behind this includes the lack of appropriate design guidelines, complex and proprietary design of composite shear connectors, lack of knowledge on the overall structural performance, and connection difficulty among composite PCSPs due to thin concrete wythes.
4. In recent years, various pultruded FRP profile sections, such as a hexagonal tube, C-shape, and I-shape have exhibited the potential of achieving higher shear strength and composite action in composite PCSPs, compared to commercially available connectors. However, investigations of these connector systems were limited to a small number of parameters and lacked knowledge of the overall structural behaviour of the panels.
5. The replacement of steel rebars with FRP reinforcement in PCSPs for enhanced durability has been identified in a few studies, but their research scope was limited to static performance under flexure and compression loads. The study on the dynamic behaviour of the PCSPs is limited, and no studies exist to address the performances of load-bearing composite PCSPs under impact and blast loading.
6. The existing research on composite PCSPs mainly concentrated on the single panel, and the study on the racking performance of the PCSP system has not been examined in detail in the existing literature.
7. Only a few research articles on the performance of connections among composite PCSPs exist in the literature. The existing connection system for buildings with non-composite PCSPs in practice adopts design from the traditional precast construction, which might be challenging in connecting composite PCSPs with thin concrete wythes. While some proprietary practices exist for connection among composite PCSPs, information on the performance of such systems is not widely available.
8. Due to the architectural design requirements, external walls are sometimes designed as curved shape walls, and the composite behaviour and the performance of shear connectors in curved PCSPs might be different from the straight PCSPs, which has not been reported so far in the literature.

Considering the present research gaps and problems associated with composite PCSPs as discussed above, future research directions could focus on.

1. Developing a more optimised design of pultruded FRP shear connectors to enhance the shear capacity and composite action between the concrete wythes.
2. Investigating the in-depth structural performance of the load-bearing FRP reinforced composite PCSPs made of sustainable materials other than conventional Portland cement concrete, such as geopolymer concrete, recycled aggregated concrete, and materials made with industrial and household wastes, under static and dynamic loads, including flexure, compression, seismic, impact and blast to establish design guidelines and promote their wide application in the construction industry.
3. Developing a more robust connection system for the panelised building using composite PCSPs and evaluating the overall structural performance of the building.
4. Designing curved PCSPs and exploring their structural behaviour to provide confidence for practical application considering architectural design flexibility.
5. Developing and testing of composite PCSP systems with respect to multi-storey fire conditions and environmental separation performance of the joining systems in service and after fire and seismic events.

CRediT authorship contribution statement

Tilak Prasad Sah: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Andrew William Lacey:** Writing – review & editing, Validation, Supervision, Conceptualization. **Hong Hao:** Writing – review & editing, Validation, Supervision, Conceptualization. **Wensu Chen:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] H. Hao, K. Bi, W. Chen, T.M. Pham, J. Li, Towards next generation design of sustainable, durable, multi-hazard resistant, resilient, and smart civil engineering structures, Eng. Struct. 277 (2023) 115477, https://doi.org/10.1016/j.engstruct.2022.115477.
[2] A.J. Sánchez-Garrido, I.J. Navarro, J. García, V. Yepes, A systematic literature review on modern methods of construction in building: an integrated approach using machine learning, J. Build. Eng. 73 (2023) 106725, https://doi.org/10.1016/j.jobe.2023.106725.
[3] S. Navaratnam, T. Ngo, T. Gunawardena, D. Henderson, Performance review of prefabricated building systems and future research in Australia, Buildings 9 (2019) 38, https://doi.org/10.3390/buildings9020038.
[4] Z. Ye, K. Giriunas, H. Sezen, G. Wu, D.-C. Feng, State-of-the-art review and investigation of structural stability in multi-story modular buildings, J. Build. Eng. 33 (2021) 101844, https://doi.org/10.1016/j.jobe.2020.101844.
[5] H.-T. Thai, T. Ngo, B. Uy, A review on modular construction for high-rise buildings, Structures 28 (2020) 1265–1290, https://doi.org/10.1016/j.istruc.2020.09.070.
[6] R.M. Lawson, R.G. Ogden, R. Bergin, Application of modular construction in high-rise buildings, J. Architect. Eng. 18 (2012) 148–154, https://doi.org/10.1061/(asce)ae.1943-5568.0000057.
[7] H. Rajanayagam, K. Poologanathan, P. Gatheeshgar, G.E. Varelis, P. Sherlock, B. Nagaratnam, et al., A-State-Of-The-Art review on modular building connections, Structures 34 (2021) 1903–1922, https://doi.org/10.1016/j.istruc.2021.08.114.
[8] PrefabAUS, Prefab in History. https://www.prefabaus.org.au/prefab-in-history. (accessed 16/June/2023)...
[9] J.Y.R. Liew, Y.S. Chua, Z. Dai, Steel concrete composite systems for modular construction of high-rise buildings, Structures 21 (2019) 135–149, https://doi.org/10.1016/j.istruc.2019.02.010.
[10] G. Perampalam, R. Dobson, K. Poologanathan, K.D. Tsavdaridis, B. Nagaratnam, E. Iacovidou, Modular building design: post-brexit housing, ce/papers 3 (2019) 219–224, https://doi.org/10.1002/cepa.1160.
[11] S. Yu, Y. Liu, D. Wang, A.S. Bahaj, Y. Wu, J. Liu, Review of thermal and environmental performance of prefabricated buildings: implications to emission reductions in China, Renew. Sustain. Energy Rev. 137 (2021) 110472, https://doi.org/10.1016/j.rser.2020.110472.
[12] G. Correia Lopes, R. Vicente, M. Azenha, T.M. Ferreira, A systematic review of Prefabricated Enclosure Wall Panel Systems: focus on technology driven for performance requirements, Sustain. Cities Soc. 40 (2018) 688–703, https://doi.org/10.1016/j.scs.2017.12.027.
[13] R.B. White, Prefabrication: a History of its Development in Great Britain, Her Majesty's Stationery Office, England, 1965.
[14] A.G.F. Gibb, Off-site Fabrication : Prefabrication, Pre-assembly and Modularisation, Whittles Publishing, Scotland, UK, 1999.
[15] PrefabAUS, What is Prefab. https://www.prefabaus.org.au/what-is-prefab. (accessed 16/June/2023)...
[16] Monash University, Handbook for the Design of Modular Structures, Monash University, Melbourne, Australia, 2017.
[17] M. Lawson, R. Ogden, C. Goodier, Design in Modular Construction, CRC Press, New York, 2014.
[18] A.W. Lacey, W. Chen, H. Hao, K. Bi, Structural response of modular buildings – an overview, J. Build. Eng. 16 (2018) 45–56, https://doi.org/10.1016/j.jobe.2017.12.008.
[19] Fib, Bulletin 43, Structural connections for precast concrete buildings, Int. Federation Struct. Concrete (fib) (2008).
[20] World Green Building Council, The Net Zero Carbon Buildings Commitment. https://worldgbc.org/thecommitment/. (accessed 18/June/2023)...
[21] Advancing Net Zero Status Report, World Green Building Council, 2022.
[22] L. Jaillon, C.S. Poon, The evolution of prefabricated residential building systems in Hong Kong: a review of the public and the private sector, Autom. ConStruct. 18 (2009) 239–248, https://doi.org/10.1016/j.autcon.2008.09.002.
[23] M. González-Torres, L. Pérez-Lombard, J.F. Coronel, I.R. Maestre, D. Yan, A review on buildings energy information: trends, end-uses, fuels and drivers, Energy Rep. 8 (2022) 626–637, https://doi.org/10.1016/j.egyr.2021.11.280.
[24] Y.H. Mugahed Amran, M. El-Zeadani, Y. Huei Lee, Y. Yong Lee, G. Murali, R. Feduik, Design innovation, efficiency and applications of structural insulated panels: a review, Structures 27 (2020) 1358–1379, https://doi.org/10.1016/j.istruc.2020.07.044.
[25] H. Tawil, C.G. Tan, N.H.R. Sulong, F.M. Nazri, M.M. Sherif, A. El-Shafie, Mechanical and thermal properties of composite precast concrete sandwich panels: a review, Buildings 12 (2022) 1429, https://doi.org/10.3390/buildings12091429.
[26] R. O'Hegarty, O. Kinnane, Review of precast concrete sandwich panels and their innovations, Construct. Build. Mater. 233 (2020) 117145, https://doi.org/10.1016/j.conbuildmat.2019.117145.
[27] Australian Bureau of Statistics, Telling Storeys-Characteristics of Apartment Building Heights, 8752.0 - Building Activity, Australia, Dec 2018, Australian Bureau of Statistics, 2019.
[28] P.A.G. Piloto, D. Vergara, Light timber framed wall under fire: effect of the load and cladding, Eng. Struct. 280 (2023) 115696, https://doi.org/10.1016/j.engstruct.2023.115696.
[29] B. Huang, K. Xing, R. Rameezdeen, Exploring embodied carbon comparison in lightweight building structure frames: a case study, Sustainability 15 (2023) 15167, https://doi.org/10.3390/su152015167.
[30] M. Premrov, V. Žegarac Leskovar, Innovative structural systems for timber buildings: a comprehensive review of contemporary solutions, Buildings 13 (2023) 1820, https://doi.org/10.3390/buildings13071820.
[31] F. Alinoori, P. Sharafi, F. Moshiri, B. Samali, Experimental investigation on load bearing capacity of full scaled light timber framed wall for mid-rise buildings, Construct. Build. Mater. 231 (2020) 117069, https://doi.org/10.1016/j.conbuildmat.2019.117069.
[32] E. Gasparri, M. Aitchison, Unitised timber envelopes. A novel approach to the design of prefabricated mass timber envelopes for multi-storey buildings, J. Build. Eng. 26 (2019) 100898, https://doi.org/10.1016/j.jobe.2019.100898.
[33] L. Kuai, S. Ormarsson, J. Vessby, R. Maharjan, A numerical and experimental investigation of non-linear deformation behaviours in light-frame timber walls, Eng. Struct. 252 (2022) 113599, https://doi.org/10.1016/j.engstruct.2021.113599.
[34] R. Mourão, A. Caçoilo, F. Teixeira-Dias, A. Montalva, H. Stone, E. Jacques, Blast resistance of timber structural elements: a state-of-the-art review, Int. J. Prot. Struct. 14 (2022) 263–295, https://doi.org/10.1177/20414196221092466.
[35] C. Viau, G. Doudak, Investigating the behavior of light-frame wood stud walls subjected to severe blast loading, J. Struct. Eng. 142 (2016) 04016138, https://doi.org/10.1061/(asce)st.1943-541x.0001622.
[36] Gosford Frames & trusses, How are wall frames erected? https://gosfordframentruss.com.au/how-are-wall-frames-erected/. (accessed 15/June/2023). .

[37] STUDCO Building Systems, Compare Steel Stud Frames and Timber Stud Frames. https://studcosystems.com.au/news-and-tech-tips/compare-steel-timber-studs/. (accessed 16/June/2023). .
[38] M. Abouhamad, M. Abu-Hamd, Life cycle environmental assessment of light steel framed buildings with cement-based walls and floors, Sustainability 12 (2020) 10686, https://doi.org/10.3390/su122410686.
[39] R.M. Lawson, ED020: Sustainability of Light Steel Construction, Light Steel Framing and Modular Construction, Silwood Park, Ascot, Steel Construction Institute, 2014, pp. 1–4.
[40] A.D. Ariyanayagam, M. Mahendran, Experimental study of non-load bearing light gauge steel framed walls in fire, J. Constr. Steel Res. 145 (2018) 529–551, https://doi.org/10.1016/j.jcsr.2018.02.023.
[41] Howick. https://www.howickltd.com/. (accessed 22/February/2023).
[42] Voestalpine Roll Forming Corporation. https://rfcorp.com/about-us/. (accessed 22/February/2023).
[43] N. Soares, P. Santos, H. Gervásio, J.J. Costa, L. Simões da Silva, Energy efficiency and thermal performance of lightweight steel-framed (LSF) construction: a review, Renew. Sustain. Energy Rev. 78 (2017) 194–209, https://doi.org/10.1016/j.rser.2017.04.066.
[44] H. Magarabooshanam, A. Ariyanayagam, M. Mahendran, Fire resistance of non-load bearing LSF walls with varying cavity depth, Thin-Walled Struct. 150 (2020) 106675, https://doi.org/10.1016/j.tws.2020.106675.
[45] Z. Yang, L. Sun, B. Nan, S. Wei, Thermal performance of slotted light steel-framed composite wall, Energies 16 (2023) 2482, https://doi.org/10.3390/en16052482.
[46] C. Liu, X. Mao, L. He, X. Chen, Y. Yang, J. Yuan, A new demountable light-gauge steel framed wall: flexural behavior, thermal performance and life cycle assessment, J. Build. Eng. 47 (2022) 103856, https://doi.org/10.1016/j.jobe.2021.103856.
[47] Y. Tao, M. Mahendran, A. Ariyanayagam, Fire tests of cold-formed steel walls made of hollow section studs, J. Constr. Steel Res. 178 (2021) 106495, https://doi.org/10.1016/j.jcsr.2020.106495.
[48] A. Aviram, R.L. Mayes, R.O. Hamburger, Innovative Steel Stud Walls for Blast Resistance, STRUCTURE Magazine (2014) 20–22.
[49] Howick, Novi Dom, Russia. https://www.howickltd.com/showcases/gallery/novi-dom-russia. (accessed 21/June/2023). .
[50] R. Purasinghe, P. Dusicka, J.S. Garth, G. Dedek, H. Lum, In-plane cyclic behavior of structural insulated panel wood walls including slit steel connectors, Eng. Struct. 174 (2018) 178–197, https://doi.org/10.1016/j.engstruct.2018.07.027.
[51] N.I. Cox, S.E. Hamel, Static modeling of plywood–polyurethane structural insulated panels in bending, J. Struct. Eng. 147 (2021) 04020334, https://doi.org/10.1061/(asce)st.1943-541x.0002915.
[52] Gluestream, ASPL-3.1 BFT Automatic SIP production line. https://gluestream.eu/product/48-automatic-line2/. (accessed 21/June/2023). .
[53] L. Bai, H. Wang, C. Shi, Q. Du, Y. Li, Assessment of SIP buildings for sustainable development in rural China using AHP-grey correlation analysis, Int. J. Environ. Res. Publ. Health 14 (2017) 1292, https://doi.org/10.3390/ijerph14111292.
[54] Structural Insulated Panel Association, Goldsmith SIP House Brunswick VIC Australia. https://www.sips.org/goldsmith-sip-house-brunswick-vic-australia?projects_by_state=1. (accessed 16/June/2023)...
[55] S. Finnegan, R. Edwards, B. Al-Derbi, I. Campbell, M. Fulton, The potential of structurally insulated panels (SIPs) to supply net zero carbon housing, Buildings 12 (2022) 2081, https://doi.org/10.3390/buildings12122081.
[56] Ł. Smakosz, J. Tejchman, Evaluation of strength, deformability and failure mode of composite structural insulated panels, Mater. Des. 54 (2014) 1068–1082, https://doi.org/10.1016/j.matdes.2013.09.032.
[57] A. Manalo, Structural behaviour of a prefabricated composite wall system made from rigid polyurethane foam and Magnesium Oxide board, Construct. Build. Mater. 41 (2013) 642–653, https://doi.org/10.1016/j.conbuildmat.2012.12.058.
[58] H. Abdolpour, J. Garzón-Roca, G. Escusa, J.M. Sena-Cruz, J.A.O. Barros, I.B. Valente, Development of a composite prototype with GFRP profiles and sandwich panels used as a floor module of an emergency house, Compos. Struct. 153 (2016) 81–95, https://doi.org/10.1016/j.compstruct.2016.05.069.
[59] L. Ding, K. Jiang, X. Wang, D. Li, Z. Wu, Z. Zhu, The effect of core materials on flexural behaviour of sandwich panels with basalt FRP facesheets, Adv. Struct. Eng. 25 (2022) 3195–3209, https://doi.org/10.1177/13694332221119860.
[60] D. Betts, P. Sadeghian, A. Fam, Experiments and nonlinear analysis of the impact behaviour of sandwich panels constructed with flax fibre-reinforced polymer faces and foam cores, J. Sandw. Struct. Mater. 23 (2020) 3139–3163, https://doi.org/10.1177/1099636220925073.
[61] A.P. Sartori, H.L. Ornaghi Junior, N.B. Guerra, P.R. Wander, M. Giovanela, R.C. Reis Nunes, et al., Development and characterization of sandwich panels for thermal insulation in a cold storage chamber, J. Cell. Plast. 59 (2023) 215–230, https://doi.org/10.1177/0021955x231162799.
[62] W. Chen, H. Hao, H. Du, Failure analysis of corrugated panel subjected to windborne debris impacts, Eng. Fail. Anal. 44 (2014) 229–249, https://doi.org/10.1016/j.engfailanal.2014.05.017.
[63] W. Chen, H. Hao, Experimental and numerical study of composite lightweight structural insulated panel with expanded polystyrene core against windborne debris impacts, Mater. Des. 60 (2014) 409–423, https://doi.org/10.1016/j.matdes.2014.04.038.
[64] W. Chen, H. Hao, Performance of structural insulated panels with rigid skins subjected to windborne debris impacts – experimental investigations, Construct. Build. Mater. 77 (2015) 241–252, https://doi.org/10.1016/j.conbuildmat.2014.12.112.
[65] Q. Meng, H. Hao, W. Chen, Laboratory test and numerical study of structural insulated panel strengthened with glass fibre laminate against windborne debris impact, Construct. Build. Mater. 114 (2016) 434–446, https://doi.org/10.1016/j.conbuildmat.2016.03.190.
[66] Q. Meng, H. Hao, W. Chen, Experimental and numerical study of basalt fibre cloth strengthened structural insulated panel under windborne debris impact, J. Reinforc. Plast. Compos. 35 (2016) 1302–1317, https://doi.org/10.1177/0731684416649787.
[67] W. Chen, H. Hao, S. Chen, F. Hernandez, Performance of composite structural insulated panel with metal skin subjected to blast loading, Mater. Des. 84 (2015) 194–203, https://doi.org/10.1016/j.matdes.2015.06.081.
[68] E.-E. Phillips, R. Murphy, J. Connors, K.F. McMullen, E. Jacques, J.C. Bruhl, Experimental evaluation of OSB-faced structural insulated panels subject to blast loads, Eng. Struct. 229 (2021) 111597, https://doi.org/10.1016/j.engstruct.2020.111597.
[69] Y. Cui, H. Hao, J. Li, W. Chen, Failure mechanism of geopolymer composite lightweight sandwich panel under flexural and edgewise compressive loads, Construct. Build. Mater. 270 (2021) 121496, https://doi.org/10.1016/j.conbuildmat.2020.121496.
[70] Victoria Government Gazette, Building Act 1993-Prohibition of High-Risk External Wall Cladding Products Declaration, IVE Group Limited, 2020.
[71] National Construction Code Volume One Amendment 1, Australian Building Codes Board, 2019.
[72] Structural Insulated Panel Association, SIP-EDG01-19 Structural Insulated Panel (SIP) Engineering Design Guide, Structural Insulated Panel Association (SIPA), Florida, 2019.
[73] A. Kermani, R. Hairstans, Racking performance of structural insulated panels, J. Struct. Eng. 132 (2006) 1806–1812.
[74] E. Jacques, J. Makar, Behavior of structural insulated panels subjected to short-term axial loads, J. Struct. Eng. 145 (2019) 04019118, https://doi.org/10.1061/(asce)st.1943-541x.0002393.
[75] A. Vaidya, N. Uddin, U. Vaidya, Structural characterization of composite structural insulated panels for exterior wall applications, J. Compos. Construct. 14 (2010) 464–469, https://doi.org/10.1061/(ASCE)CC.1943-5614.0000037.
[76] M.A. Mousa, N. Uddin, Global buckling of composite structural insulated wall panels, Mater. Des. 32 (2011) 766–772, https://doi.org/10.1016/j.matdes.2010.07.026.
[77] Creative Mechanisms Staff, Everything You Need to Know about Polypropylene (PP) Plastic, 2016. https://www.creativemechanisms.com/blog/all-about-polypropylene-pp-plastic#:~:text=Polypropylene%20is%20highly%20flammable. (Accessed 15 June 2023).
[78] A.B. Cuevas, Fire and Structural Performance of Structural Insulated Panels [PhD Thesis], The University of Queensland, 2019.
[79] A. Manalo, T. Aravinthan, A. Fam, B. Benmokrane, State-of-the-Art review on FRP sandwich systems for lightweight civil infrastructure, J. Compos. Construct. 21 (2017) 04016068, https://doi.org/10.1061/(asce)cc.1943-5614.0000729.
[80] D. Hristozov, L. Wroblewski, P. Sadeghian, Durability of Flax FRPs Exposed to Accelerated Environmental Conditions, CDCC, Sherbrooke, Quebec, 2017 CanadaJuly 19-21.
[81] A. Michel Murillo, G. Valery Abisambra, P. Aura Acosta, Q. Claudia Quesada, B.F. Tutikian, H.Z. Ehrenbring, Comparison of the fire resistance behaviour of

structural insulated panels with expanded polystyrene core treated with intumescent coating, J. Mater. Res. Technol. 12 (2021) 1958–1969, https://doi.org/10.1016/j.jmrt.2021.03.079.

[82] P.L.N. Fernando, M.T.R. Jayasinghe, C. Jayasinghe, Structural feasibility of Expanded Polystyrene (EPS) based lightweight concrete sandwich wall panels, Construct. Build. Mater. 139 (2017) 45–51, https://doi.org/10.1016/j.conbuildmat.2017.02.027.

[83] Y. Cui, H. Hao, J. Li, W. Chen, X. Zhang, Structural behavior and vibration characteristics of geopolymer composite lightweight sandwich panels for prefabricated buildings, J. Build. Eng. 57 (2022) 104872, https://doi.org/10.1016/j.jobe.2022.104872.

[84] T. Bhat, V. Chevali, X. Liu, S. Feih, A.P. Mouritz, Fire structural resistance of basalt fibre composite, Compos. A: Appl. Sci. Manuf. 71 (2015) 107–115, https://doi.org/10.1016/j.compositesa.2015.01.006.

[85] C. Peng, Y.J. Kim, J. Zhang, Thermal and energy characteristics of composite structural insulated panels consisting of glass fiber reinforced polymer and cementitious materials, J. Build. Eng. 43 (2021) 102483, https://doi.org/10.1016/j.jobe.2021.102483.

[86] A. Crampton, Cross Laminated Timber: the Future of Mid-rise Construction, Portland State University, Center for Real Estate Quarterly Report, vol. 10, 2016 Number 3.

[87] A. Younis, A. Dodoo, Cross-laminated timber for building construction: a life-cycle-assessment overview, J. Build. Eng. 52 (2022) 104482, https://doi.org/10.1016/j.jobe.2022.104482.

[88] F. Brandstätter, K. Kalbe, M. Autengruber, M. Lukacevic, T. Kalamees, A. Ruus, et al., Numerical simulation of CLT moisture uptake and dry-out following water infiltration through end-grain surfaces, J. Build. Eng. 80 (2023) 108097, https://doi.org/10.1016/j.jobe.2023.108097.

[89] J. Ou, Z. Chen, W. Long, D. Chen, L. Huo, Y. Zhang, Research on stability of CLT wall under uniform compression based on orthotropic plate buckling theory, J. Build. Eng. 84 (2024) 108571, https://doi.org/10.1016/j.jobe.2024.108571.

[90] D. Fanella, Cost Comparison of Cross Laminated Timber (CLT) and Cast-In-Place Reinforced Concrete Structures, CRSI Technical Note ETND-5-18, Schaumburg, Illinois, Concrete Reinforcing Steel Institute, 2018, p. 4.

[91] Y. Pan, T. Teflissi, T. Tannert, Experimental parameter study on CLT shear walls with self-tapping screw connections, J. Struct. Eng. 150 (2024) 04023192, https://doi.org/10.1061/jsendh.Steng-12710.

[92] E. Karacabeyli, B. Douglas, CLT handbook, in: U.S. ed., FPInnovation, Quebec, Canada, 2013.

[93] XLAM, Adelaide Oval Hotel. https://xlam.co/case-studies/adelaide-oval-hotel. (accessed 12/May/2023). .

[94] T. Faria Oliveira, J.M.F. de Carvalho, J. Castro Mendes, G. Zuqui Souza, V. Rezende Carvalho, R. André Fiorotti Peixoto, Precast concrete sandwich panels (PCSP): an analytical review and evaluation of CO2 equivalent, Construct. Build. Mater. 358 (2022) 129424, https://doi.org/10.1016/j.conbuildmat.2022.129424.

[95] Fib, Bulletin-84, Precast insulated sandwich panels- State-of-the-art report, Int. Federation Struct. Concrete (fib) (2017).

[96] A. Einea, D.C. Salmon, G.J. Fogarasi, T.D. Culp, M.K. Tadros, State-of-the-Art of precast concrete sandwich panels, PCI J. 36 (1991) 78–98, https://doi.org/10.15554/pcij.11011991.78.98.

[97] Q. Tushar, G. Zhang, M.A. Bhuiyan, S. Navaratnam, F. Giustozzi, L. Hou, Retrofit of building façade using precast sandwich panel: an integrated thermal and environmental assessment on BIM-based LCA, Buildings 12 (2022) 2098, https://doi.org/10.3390/buildings12122098.

[98] T. Vasishta, M. Hashem Mehany, J. Killingsworth, Comparative life cycle assesment (LCA) and life cycle cost analysis (LCCA) of precast and cast–in–place buildings in United States, J. Build. Eng. 67 (2023) 105921, https://doi.org/10.1016/j.jobe.2023.105921.

[99] SPEC-NET, Concrete sandwich panel insulation for ravenhall by CGS, https://www.spec-net.com.au/press/0421/cgs_210421/Concrete-Sandwich-Panel-Insulation-for-Ravenhall-by-CGS, 2017. (Accessed 2 June 2023).

[100] G. Gardiner, CompositesWorld, Higher performance in precast concrete with CFRP, https://www.compositesworld.com/articles/higher-performance-in-precast-concrete-with-cfrp, 2017.

[101] S. Pessiki, A. Mlynarczyk, Experimental evaluation of the composite behavior of precast concrete sandwich wall panels, PCI J. (2003) 54–71, https://doi.org/10.15554/pcij.03012003.54.71.

[102] Candaian Precast/Prestressed Concrete Institute, CPCI Design Manual, fifth ed., Candaian Precast/Prestressed Concrete Institute, Ottawa, Canada, 2017.

[103] B. Johnson, International institute of building enclosure consultants, composite precast concrete sandwich wall panels: get more from your wall system using less, https://iibec.org/composite-precast-sandwich/, 2021. (Accessed 29 May 2023).

[104] P. Pan, Z. He, H. Wang, Y. Kang, Experimental investigation of C-shaped glass-fiber-reinforced polymer connectors for sandwich insulation wall panels, Eng. Struct. 250 (2022) 113462, https://doi.org/10.1016/j.engstruct.2021.113462.

[105] J.-Q. Huang, J.-G. Dai, Flexural performance of precast geopolymer concrete sandwich panel enabled by FRP connector, Compos. Struct. 248 (2020) 112563, https://doi.org/10.1016/j.compstruct.2020.112563.

[106] Q. Huang, E. Hamed, R.I. Gilbert, Behavior of concrete sandwich panels under eccentric axial compression-testing and finite element analysis, ACI Struct. J. 117 (2020) 235–247, https://doi.org/10.14359/51723502.

[107] E. Hamed, D. Negru, R. Yalda, Structural performance of precast concrete sandwich panels made with FRP vierendeel truss–like connectors, J. Compos. Construct. 26 (2022) 04022027, https://doi.org/10.1061/(asce)cc.1943-5614.0001215.

[108] Q. Huang, E. Hamed, Nonlinear finite element analysis of composite precast concrete sandwich panels made with diagonal FRP bar connectors, Compos. Struct. 212 (2019) 304–316, https://doi.org/10.1016/j.compstruct.2019.01.019.

[109] R. O'Hegarty, O. Kinnane, S.J. McCormack, Concrete solar collectors for façade integration: an experimental and numerical investigation, Appl. Energy 206 (2017) 1040–1061, https://doi.org/10.1016/j.apenergy.2017.08.239.

[110] S. Kumar, B. Chen, Y. Xu, J.-G. Dai, Axial-flexural behavior of FRP grid-reinforced geopolymer concrete sandwich wall panels enabled with FRP connectors, J. Build. Eng. 47 (2022) 103907, https://doi.org/10.1016/j.jobe.2021.103907.

[111] S. Kumar, B. Chen, Y. Xu, J.-G. Dai, Structural behavior of FRP grid reinforced geopolymer concrete sandwich wall panels subjected to concentric axial loading, Compos. Struct. 270 (2021) 114117, https://doi.org/10.1016/j.compstruct.2021.114117.

[112] Y.H. Mugahed Amran, A.A. Abang Ali, R.S.M. Rashid, F. Hejazi, N.A. Safiee, Structural behavior of axially loaded precast foamed concrete sandwich panels, Construct. Build. Mater. 107 (2016) 307–320, https://doi.org/10.1016/j.conbuildmat.2016.01.020.

[113] J. Xie, F. Chen, J. Zhao, P. Lu, F. Liu, L. Li, Flexural behaviour of full-scale precast recycled concrete sandwich panels with BFRP connectors, J. Build. Eng. 56 (2022) 104816, https://doi.org/10.1016/j.jobe.2022.104816.

[114] N. Williams Portal, M. Flansbjer, K. Zandi, L. Wlasak, K. Malaga, Bending behaviour of novel Textile Reinforced Concrete-foamed concrete (TRC-FC) sandwich elements, Compos. Struct. 177 (2017) 104–118, https://doi.org/10.1016/j.compstruct.2017.06.051.

[115] Q. Huang, E. Hamed, R. Ian Gilbert, Experimental and numerical investigation of the creep response of precast concrete sandwich panels, Structures 28 (2020) 2096–2110, https://doi.org/10.1016/j.istruc.2020.10.039.

[116] R. Ding, Y.-T. Sun, J.-S. Fan, D.-Q. Chen, Experimental and theoretical study on flexural behaviour of a new UHPC sandwich slab, Eng. Struct. 267 (2022) 114673, https://doi.org/10.1016/j.engstruct.2022.114673.

[117] CROSS Safety Report, Defects Found in Precast (Prefabricated) Concrete Façades, CROSS-AUS, 2023.

[118] A. Garhwal, S. Sharma, D. Roy A B, Performance of Expanded Polystyrene (EPS) sandwiched concrete panels subjected to accelerated corrosion, Structures 43 (2022) 1057–1072, https://doi.org/10.1016/j.istruc.2022.07.020.

[119] D. Tomlinson, A. Fam, Combined loading behavior of basalt FRP–reinforced precast concrete insulated partially-composite walls, J. Compos. Construct. 20 (2016) 04015060, https://doi.org/10.1061/(asce)cc.1943-5614.0000611.

[120] J.-Q. Huang, Y.-Y. Xu, H. Huang, J.-G. Dai, Structural behavior of FRP connector enabled precast geopolymer concrete sandwich panels subjected to one-side fire exposure, Fire Saf. J. 128 (2022) 103524, https://doi.org/10.1016/j.firesaf.2022.103524.

[121] X. Liu, X. Wang, T. Yang, Z. Wu, The shear behavior of insulated precast concrete sandwich panels reinforced with BFRP, Buildings 12 (2022) 1326, https://doi.org/10.3390/buildings12091326.

[122] P. Syndergaard, R. Tawadrous, S. Al-Rubaye, M. Maguire, Comparing testing methods of partially composite sandwich wall panel glass fiber–reinforced polymer connectors, J. Compos. Construct. 26 (2022) 04021070, https://doi.org/10.1061/(asce)cc.1943-5614.0001181.

[123] G. Woltman, D. Tomlinson, A. Fam, Investigation of various GFRP shear connectors for insulated precast concrete sandwich wall panels, J. Compos. Construct. 17 (2013) 711–721, https://doi.org/10.1061/(asce)cc.1943-5614.0000373.

[124] D. Chen, K. Li, Z. Yuan, B. Cheng, X. Kang, Shear behavior of FRP connectors in precast sandwich insulation wall panels, Buildings 12 (2022) 1095, https://doi.org/10.3390/buildings12081095.

[125] X. Lou, W. Xue, H. Bai, Y. Li, Q. Huang, Shear behavior of stainless-steel plate connectors for insulated precast concrete sandwich panels, Structures 44 (2022) 1046–1056, https://doi.org/10.1016/j.istruc.2022.08.073.

[126] K. Hodicky, G. Sopal, S. Rizkalla, T. Hulin, H. Stang, Experimental and numerical investigation of the FRP shear mechanism for concrete sandwich panels, J. Compos. Construct. 19 (2015) 04014083, https://doi.org/10.1061/(ASCE)CC.1943-5614.0000554.

[127] K.-B. Choi, W.-C. Choi, L. Feo, S.-J. Jang, H.-D. Yun, In-plane shear behavior of insulated precast concrete sandwich panels reinforced with corrugated GFRP shear connectors, Compos. B Eng. 79 (2015) 419–429, https://doi.org/10.1016/j.compositesb.2015.04.056.

[128] O. Kinnane, R. West, R.O. Hegarty, Structural shear performance of insulated precast concrete sandwich panels with steel plate connectors, Eng. Struct. 215 (2020) 110691, https://doi.org/10.1016/j.engstruct.2020.110691.

[129] S. Al-Rubaye, T. Sorensen, J. Olsen, M. Maguire, Evaluating elastic behavior for partially composite precast concrete sandwich wall panels, PCI J. 63 (2018) 71–88, https://doi.org/10.15554/pcij63.5-04.

[130] J. Olsen, M. Maguire, Shear Testing of Precast Concrete Sandwich Wall Panel Composite Shear Connectors, PCI J, 2016.

[131] H. Jiang, Z. Guo, J. Liu, H. Liu, The shear behavior of precast concrete sandwich panels with W-shaped SGFRP shear connectors, KSCE J. Civ. Eng. 22 (2018) 3961–3971, https://doi.org/10.1007/s12205-018-0809-9.

[132] H. Jiang, Z. Guo, J. Liu, Composite behavior of sandwich panels with W-shaped SGFRP connectors, KSCE J. Civ. Eng. 22 (2017) 1889–1899, https://doi.org/10.1007/s12205-017-2050-3.

[133] J.-Q. Huang, J.-G. Dai, Direct shear tests of glass fiber reinforced polymer connectors for use in precast concrete sandwich panels, Compos. Struct. 207 (2019) 136–147, https://doi.org/10.1016/j.compstruct.2018.09.017.

[134] Z. He, P. Pan, J. Ren, H. Wang, Experimental and numerical investigation of novel I-shaped GFRP connectors for insulated precast concrete sandwich wall panels, J. Compos. Construct. 24 (2020) 04020040, https://doi.org/10.1061/(asce)cc.1943-5614.0001053.

[135] C.P. Pantelides, R. Surapaneni, L.D. Reaveley, Structural performance of hybrid GFRP/steel concrete sandwich panels, J. Compos. Construct. 12 (2008) 570–576.

[136] T.D. Bush, G.L. Stine, Flexural behavior of composite precast concrete sandwich panels with continuous truss connectors, PCI J. 39 (1994) 112–121, https://doi.org/10.15554/pcij.03011994.112.121.

[137] D.-H. Shin, H.-J. Kim, Composite effects of shear connectors used for lightweight-foamed-concrete sandwich wall panels, J. Build. Eng. 29 (2020) 101108, https://doi.org/10.1016/j.jobe.2019.101108.

[138] Y. Wang, J. Wang, D. Zhao, G. Hota, R. Liang, D. Hui, et al., Flexural behavior of insulated concrete sandwich panels using FRP-jacketed steel-composite connectors, Adv. Mater. Sci. Eng. 2022 (2022) 1–25, https://doi.org/10.1155/2022/6160841.

[139] N. Goudarzi, Y. Koarny, S. Adeeb, R. Cheng, Flexural behaviour of highly composite nonloadbearing precast concrete sandwich panels, Resilient Infrastructure, London, CSCE (June 1–4) (2016).

[140] N. Goudarzi, Y. Korany, S. Adeeb, R. Cheng, Characterization of the shear behavior of Z-shaped steel plate connectors used in insulated concrete panels, PCI J. 61 (2016) 23–37, https://doi.org/10.15554/pcij.03012016.23.37.

[141] I. Choi, J. Kim, Y.-C. You, Effect of cyclic loading on composite behavior of insulated concrete sandwich wall panels with GFRP shear connectors, Compos. B Eng. 96 (2016) 7–19, https://doi.org/10.1016/j.compositesb.2016.04.030.

[142] T.G. Norris, A. Chen, Development of insulated FRP-confined Precast Concrete Sandwich panel with side and top confining plates and dry bond, Compos. Struct. 152 (2016) 444–454, https://doi.org/10.1016/j.compstruct.2016.05.053.

[143] D. Dutta, A. Jawdhari, A. Fam, A new studded precast concrete sandwich wall with embedded glass-fiber-reinforced polymer channel sections, Part 1, experimental study, PCI J. 65 (2020) 78–99, https://doi.org/10.15554/pcij65.3-04.

[144] Y. Chen, C. Kang, Y. Wu, Z. Qian, Bending performance of precast ceramsite-concrete-insulated sandwich panel with stainless steel shear connectors, Buildings 12 (2022) 1640, https://doi.org/10.3390/buildings12101640.

[145] H. Hou, K. Ji, W. Wang, B. Qu, M. Fang, C. Qiu, Flexural behavior of precast insulated sandwich wall panels: full-scale tests and design implications, Eng. Struct. 180 (2019) 750–761, https://doi.org/10.1016/j.engstruct.2018.11.068.

[146] M.J. Gombeda, C.J. Naito, S.E. Quiel, Flexural performance of precast concrete insulated wall panels with various configurations of ductile shear ties, J. Build. Eng. 33 (2021) 101574, https://doi.org/10.1016/j.jobe.2020.101574.

[147] J. Luebke, F.F. Pozo-Lora, S. Al-Rubaye, M. Maguire, Out-of-Plane flexural behavior of insulated wall panels constructed with large insulation thicknesses, Materials 16 (2023) 4160, https://doi.org/10.3390/ma16114160.

[148] J.-Q. Huang, Q. Jiang, X. Chong, C.-L. Zhao, Z.-Y. Wang, Structural performance and section optimization of precast concrete sandwich panels with pin-type GFRP connectors, Adv. Struct. Eng. 24 (2021) 2351–2363, https://doi.org/10.1177/1369433221999769.

[149] I. Choi, J. Kim, H.R. Kim, Composite behavior of insulated concrete sandwich wall panels subjected to wind pressure and suction, Materials 8 (2015) 1264–1282, https://doi.org/10.3390/ma8031264.

[150] R. O'Hegarty, O. Kinnane, M. Grimes, J. Newell, M. Clifford, R. West, Development of thin precast concrete sandwich panels: challenges and outcomes, Construct. Build. Mater. 267 (2021) 120981, https://doi.org/10.1016/j.conbuildmat.2020.120981.

[151] A.B. Awan, F.U.A. Shaikh, Compressive behavior of precast concrete sandwich panels containing recycled tyre crumb rubber core, Struct. Concr. 23 (2021) 2786–2802, https://doi.org/10.1002/suco.202100470.

[152] F. Gara, L. Ragni, D. Roia, L. Dezi, Experimental tests and numerical modelling of wall sandwich panels, Eng. Struct. 37 (2012) 193–204, https://doi.org/10.1016/j.engstruct.2011.12.027.

[153] J. Daniel Ronald Joseph, J. Prabakar, P. Alagusundaramoorthy, Experimental and analytical investigations on the failure modes of concrete sandwich panels under axial compression, Eur. J. Environ. Civ. Eng. 27 (2022) 733–762, https://doi.org/10.1080/19648189.2022.2063948.

[154] W. Qiao, W. Tian, J. Yuan, D. Wang, J. Yuan, L. Meng, Study on axial compression bearing capacity of in-sulated sandwich concrete wall with embedded columns, Adv. Struct. Eng. (2022) 1–21 https://doi.org/10.1177/13694332221133201, 0.

[155] D.G. Tomlinson, N. Teixeira, A. Fam, New shear connector design for insulated concrete sandwich panels using basalt fiber-reinforced polymer bars, J. Compos. Construct. 20 (2016) 04016003, https://doi.org/10.1061/(asce)cc.1943-5614.0000662.

[156] V. Sylaj, A. Fam, UHPC sandwich panels with GFRP shear connectors tested under combined bending and axial loads, Eng. Struct. 248 (2021) 113287, https://doi.org/10.1016/j.engstruct.2021.113287.

[157] A. Pavese, D.A. Bournas, Experimental assessment of the seismic performance of a prefabricated concrete structural wall system, Eng. Struct. 33 (2011) 2049–2062, https://doi.org/10.1016/j.engstruct.2011.02.043.

[158] S. Ma, D. Hou, P. Bao, D. Wang, Influence of alkali-resistant glass fiber on seismic performance of precast ceramsite concrete sandwich wall panels, Structures 38 (2022) 94–107, https://doi.org/10.1016/j.istruc.2022.01.081.

[159] Z. Lu, Y. Wang, J. Li, L. Wang, Experimental study on seismic performance of L-shaped insulated concrete sandwich shear wall with a horizontal seam, Struct. Des. Tall Special Build. 28 (2019) e1551, https://doi.org/10.1002/tal.1551.

[160] M. Haffke, M. Pahn, C. Thiele, S. Grzesiak, Experimental investigation of concrete sandwich walls with glass-fiber-composite connectors exposed to fire and mechanical loading, Appl. Sci. 12 (2022) 3872, https://doi.org/10.3390/app12083872.

[161] K.J. Kontoleon, K. Georgiadis-Filikas, K.G. Tsikaloudaki, T.G. Theodosiou, C.S. Giarma, C.G. Papanicolaou, et al., Vulnerability assessment of an innovative precast concrete sandwich panel subjected to the ISO 834 fire, J. Build. Eng. 52 (2022) 104479, https://doi.org/10.1016/j.jobe.2022.104479.

[162] C. Naito, M. Beacraft, J. Hoemann, J. Shull, H. Salim, B. Bewick, Blast performance of single-span precast concrete sandwich wall panels, J. Struct. Eng. 140 (2014) 04014096, https://doi.org/10.1061/(ASCE)ST.1943-541X.0001020.

[163] A. Abbas, M. Adil, N. Ahmad, I. Ahmad, Behavior of reinforced concrete sandwiched panels (RCSPs) under blast load, Eng. Struct. 181 (2019) 476–490,

https://doi.org/10.1016/j.engstruct.2018.12.051.
[164] Y. Yang, Z. Ge, Y. Li, Y. Xiong, Q. Yuan, Study on impact resistance of precast light-weight concrete sandwich panels, Structures 47 (2023) 966–975, https://doi.org/10.1016/j.istruc.2022.11.112.
[165] Y. Yang, Z. Ge, Y. Li, X. Fan, Investigation on mechanical properties of lightweight sandwich exterior wall with thermal blocking shear connector, Structures 46 (2022) 421–432, https://doi.org/10.1016/j.istruc.2022.10.064.
[166] A. Buchanan, D. Carradine, G. Beattie, H. Morris, Performance of houses during the christchurch earthquake of 22 february 2011, Bull. N. Z. Soc. Earthq. Eng. 44 (2011) 342–357, https://doi.org/10.5459/bnzsee.44.4.342-357.
[167] SleepingGiant65, Tilt-up concrete ain't for the weak of heart, https://www.reddit.com/r/Construction/comments/2c2yjf/tiltup_concrete_aint_for_the_weak_of_heart/, 2014. (Accessed 1 May 2023).
[168] ICONXUSA. https://iconxusa.com/insulation-choices.
[169] M. Maguire, S. Al-Rubaye, Tilt-Up Partially Composite Insulated Wall Panels, University of Nebraska-Lincoln, 2022, https://doi.org/10.32873/unl.dc.oth.014.
[170] E. Henin, G. Morcous, M.K. Tadros, Precast/Prestressed concrete sandwich panels for thermally efficient floor/roof applications, Pract. Period. Struct. Des. Construct. 19 (2014) 04014013, https://doi.org/10.1061/(asce)sc.1943-5576.0000213.
[171] S. Gerges, P. Gkorogias, Concrete Sandwich Element Design in Terms of Passive Housing Recommendations and Moisture Safety [Master Thesis], Kungliga Tekniska Högskolan, Sweden, 2015.
[172] Australian modern building alliance, Reference 1: Physical properties of polyurethane insulation, Australia, Chem. Aust. 1 (2021).
[173] Airium, Insulation redefined. https://www.airium.com/#About-AIRIUM. (accessed 29/May/2023). .
[174] S. Schiavoni, F. D′Alessandro, F. Bianchi, F. Asdrubali, Insulation materials for the building sector: a review and comparative analysis, Renew. Sustain. Energy Rev. 62 (2016) 988–1011, https://doi.org/10.1016/j.rser.2016.05.045.
[175] Standards Australia, AS/NZS 1170.0:2002 Structural Design Actions Part 0: General Principles, Standards Australia, 2002.
[176] Standards Australia, AS 1170.2: 2021 Structural Design Actions Part 2: Wind Actions, Standards Australia, 2021.
[177] European Standard, EN 1991-1-7 (2006), Eurocode 1: Actions on Structures - Part 1-7: General Actions - Accidental Actions, European committee for standardization, 2006.
[178] WorkSafe Victoria, Precast and Tilt-Up Concrete for Buildings, WorkSafe Victoria, Melbourne, Australia. .
[179] Australian Building Codes Board, National Construction Code Handbook-Structural Robustness, Australian Building Codes Board, Canberra, Australia, 2020.
[180] J.-X. He, Z.-D. Xu, L.-Y. Zhang, Z.-H. Lin, Z.-W. Hu, Q.-Q. Li, et al., Shaking table tests and seismic assessment of a full-scale precast concrete sandwich wall panel structure with bolt connections, Eng. Struct. 278 (2023) 115543, https://doi.org/10.1016/j.engstruct.2022.115543.
[181] L. Jin, M. Xia, R. Zhang, M. Lin, X. Du, Computational modeling and dynamic response of reinforced concrete shear wall under out-of-plane impact loading, Int. J. Impact Eng. 172 (2023) 104425, https://doi.org/10.1016/j.ijimpeng.2022.104425.
[182] R. Zhang, M. Lin, L. Jin, X. Du, Influence of axial load and transverse impact velocity on the behavior of concrete shear walls reinforced with GFRP bars, J. Compos. Construct. 27 (2023) 04023013, https://doi.org/10.1061/jccof2.Cceng-4095.
[183] C. Shi, J. Zhang, J. Zhang, F. Shao, Y. Zhang, M. Zhang, et al., Experimental study and numerical analysis on impact resistance of civil air defense engineering shear wall, Adv. Civ. Eng. 2021 (2021) 1–20, https://doi.org/10.1155/2021/7376909.
[184] X. Ye, C. Zhao, K. He, L. Zhou, X. Li, J. Wang, Blast behaviors of precast concrete sandwich EPS panels: FEM and theoretical analysis, Eng. Struct. 226 (2021) 111345, https://doi.org/10.1016/j.engstruct.2020.111345.
[185] P.M. Hopkins, A. Chen, M. Yossef, Static and dynamic analyses of insulated concrete sandwich panels using a unified non-linear finite element model, Eng. Struct. 132 (2017) 249–259, https://doi.org/10.1016/j.engstruct.2016.11.017.
[186] J.M. Nickerson, P.A. Trasborg, C.J. Naito, C.M. Newberry, J.S. Davidson, Finite element evaluation of blast design response criteria for load-bearing precast wall panels, Int. J. Prot. Struct. 6 (2015) 155–173, https://doi.org/10.1260/2041-4196.6.1.155.
[187] C.J. Naito, J.M. Hoemann, J.S. Shull, A. Saucier, H.A. Salim, B.T. Bewick, et al., Precast/prestressed concrete experiments performance on non-load bearing sandwich wall panels, USA, Air force research laboratory materials and manufacturing directorate, AFRL-RX-TY-TR-2011-0021 (2011).
[188] J. Wang, Q. Shen, B. Li, Seismic behavior investigation on blind bolted CFST frames with precast SCWPs, Int. J. Steel Struct. 18 (2018) 1666–1683, https://doi.org/10.1007/s13296-018-0068-0.
[189] C. de Sousa, J.A.O. Barros, J.R. Correia, In-plane cyclic behaviour of RC frames strengthened with composite sandwich panels, Eng. Struct. 251 (2022) 113529, https://doi.org/10.1016/j.engstruct.2021.113529.
[190] Major fire engulfs skyscraper in Changsha, central China, Guardian. 2022. https://www.theguardian.com/world/2022/sep/16/major-fire-breaks-out-at-skyscraper-in-changsha-china. (Accessed 1 May 2023).
[191] J. Chen, E. Hamed, R.I. Gilbert, Structural performance of concrete sandwich panels under fire, Fire Saf. J. 121 (2021) 103293, https://doi.org/10.1016/j.firesaf.2021.103293.
[192] PCI Design Handbook, seventh ed., Precast/Prestressed Concrete Institute, 2010.
[193] J.M. Wenke, C.W. Dolan, Structural integrity of precast concrete modular construction, PCI J. 66 (2021) 58–70, https://doi.org/10.15554/pcij66.2-02.
[194] T. Gunawardena, Behaviour of Prefabricated Modular Buildings Subjected to Lateral Loads [PhD Thesis], The University of Melbourne, 2016.
[195] B. Yön, E. Sayın, O. Onat. Earthquakes and structural damages. In: Zouaghi T, editor. Earthquakes - Tectonics, Hazard and Risk Mitigation2017. https://doi.org/10.5772/65425.
[196] Peikko, PD Diagonal Tie. https://www.peikko.com.au/products/product/pd-diagonal-tie/photos-and-videos/. (accessed 29/May/2023). .
[197] J. Straube, High-Performing Precast Concrete Building Enclosures: Rain Control, Building Science Corporation, Ontario, Canada, 2013, pp. 1–48.
[198] M. Lentzkow, Tilt-Up Concrete Association, Rain screens: Tilt-Up facade options for achieving barrier conditions, https://tilt-up.org/tilt-uptoday/2020/02/21/rain-screens-tilt-up-facade-options-for-achieving-barrier-conditions/, 2020. (Accessed 7 February 2024).
[199] Fib, Bulletin-88-Sustainability of precast structures, Int. Federation Struct. Concrete (fib) (2018).
[200] G. Woltman, M. Noel, A. Fam, Experimental and numerical investigations of thermal properties of insulated concrete sandwich panels with fiberglass shear connectors, Energy Build. 145 (2017) 22–31, https://doi.org/10.1016/j.enbuild.2017.04.007.
[201] L. Peng, L. Xiaoyong, C. Ying, Y. Zhiwu, Y. Dayou, Thermodynamic and acoustic behaviors of prefabricated composite wall panel, Structures 28 (2020) 1301–1313, https://doi.org/10.1016/j.istruc.2020.09.069.
[202] B. Hubbs, E. Guetter, Precast Concrete Construction: from Pitfalls to High Performance, 31st RCI International Convention and Trade Show, Orlando, United States, 2016.
[203] X. Lu, T. Lu, V. Penttalac, T. Lehtinend, Study of heat and moisture transport for concrete sandwich panel wall construction, Build. Serv. Eng. Res. Technol. 25 (2002) 89–98.
[204] R. O'Hegarty, A. Reilly, R. West, O. Kinnane, Thermal investigation of thin precast concrete sandwich panels, J. Build. Eng. 27 (2020) 100937, https://doi.org/10.1016/j.jobe.2019.100937.
[205] S. Yu, Y. Liu, D. Wang, C. Ma, J. Liu, Theoretical, experimental and numerical study on the influence of connectors on the thermal performance of precast concrete sandwich walls, J. Build. Eng. 57 (2022) 104886, https://doi.org/10.1016/j.jobe.2022.104886.
[206] E. Hamed, Modeling, analysis, and behavior of load-carrying precast concrete sandwich panels, J. Struct. Eng. 142 (2016) 04016036, https://doi.org/10.1061/(asce)st.1943-541x.0001490.
[207] PCI Committee on precast sandwich wall panels, State of the Art of Precast/prestressed Concrete Sandwich Wall Panels, 2011 PCI.
[208] T.K. Hassan, S.H. Rizkalla, Analysis and design guidelines of precast prestressed concrete composite load-bearing sandwich wall panels reinforced with CFRP grid, PCI J. 55 (2010) 147–162, https://doi.org/10.15554/pcij.03012010.147.162.
[209] D. Tomlinson, A. Fam, Analysis and parametric study of partially composite precast concrete sandwich panels under axial loads, J. Struct. Eng. 142 (2016) 04016086, https://doi.org/10.1061/(ASCE)ST.1943-541X.0001560.
[210] M.J. Gombeda, P. Trasborg, C.J. Naito, S.E. Quiel, Simplified model for partially-composite precast concrete insulated wall panels subjected to lateral loading, Eng. Struct. 138 (2017) 367–380, https://doi.org/10.1016/j.engstruct.2017.01.065.

[211] C.M. Newberry, J.M. Hoemann, B.T. Bewick, J.S. Davidson, Response prediction of foam-insulated concrete sandwich panels subjected to blast loads using bilinear weighted-resistance SDOF models, Int. J. Prot. Struct. 3 (2012) 389–405, https://doi.org/10.1260/2041-4196.3.4.389.
[212] A. Jawdhari, A. Fam, A new studded precast concrete sandwich wall with embedded glass-fiber-reinforced polymer channel sections: Part 2, finite element analysis and parametric studies, PCI J. 65 (2020) 51–70, https://doi.org/10.15554/pcij65.4-02.
[213] A. Alchaar, F. Abed, Finite element analysis of a thin-shell concrete sandwich panel under eccentric loading, J. Build. Eng. 32 (2020) 101804, https://doi.org/10.1016/j.jobe.2020.101804.