Optimised Cold-Formed Steel Beams in Modular Building Applications

Perampalam Gatheeshgar
Faculty of Engineering and Environment, Northumbria University,
Newcastle upon Tyne, UK.

Keerthan Poologanathan
Faculty of Engineering and Environment, Northumbria University,
Newcastle upon Tyne, UK.

Shanmuganathan Gunalan
School of Engineering and Built Environment, Griffith University,
Gold Coast, QLD, Australia.

Konstantinos Daniel Tsavdaridis
School of Civil Engineering, Faculty of Engineering, University of Leeds
Leeds, UK.

Brabha Nagaratnam
Faculty of Engineering and Environment, Northumbria University,
Newcastle upon Tyne, UK.

Eleni Iacovidou
Institute of Environment, Health and Sciences, College of Health and Life Sciences, Brunel University London, London, UK.

Abstract

Modular Building Systems (MBS) has seen an accelerating growth in the construction sector owing to its potential advantages, such as quick erection, improved energy efficiency and less reliant on good weather over conventional construction methods. Therefore, it could be a viable solution to supporting the efforts of solving Britain's housing crisis within a short duration. Construction industries and researchers are working towards better understanding MBS performance at different scales and contexts. To date, research on MBS focused on investigating the structural, social and economic, and safety performances and indicated that there are challenges (Need of lightweight materials and more access space, transportation restrictions, improving structural, fire and energy performances) associated with their use, yet to be addressed. This paper highlights how the incorporation of optimised Cold-Formed Steel (CFS) members with the slotted web can address these challenges. Hence, optimisation technique was employed to enhance the structural performance and to effectively use the given amount of material of CFS members. Lipped channel, folded-flange, and super-sigma have been optimised using the Particle Swarm Optimisation (PSO) method and were analysed using FEM. Results showed that the flexural capacity of the optimised sections was improved by 30-65% compared to conventional CFS sections. A conceptual design of MBS was developed using the optimised CFS members, demonstrating the potential for lighter modules and thus more sustainable structures, reducing the carbon footprint. Therefore, optimisation techniques and slotted perforations would address the aforementioned challenges related to MBS, result in more economical and efficient MBS for inhabitants and construction industries.

Keywords: Modular Construction and Challenges, Cold-Formed Steel, Innovative Sections with Slotted Web, Particle Swarm Optimisation, Finite Element Analyses, Conceptual Design

1 Introduction

Modular construction, also known as off-site construction, is a process where individual modules manufactured off-site are subsequently transported and assembled on-site. By the use of this method more than three-quarters of the construction phase is completed off-site, generating environmental and economic savings [1, 2]. MBS has recently attracted a lot of attention due to its numerous advantages of speed erection, improved quality, reduced waste generation, reduced cost, improved sustainability, less on-site noise generation as described in many studies [1, 2,5-12]. Among the MBS advantages, the reduced construction time over conventional construction methods has gained the attention of the UK government and construction industry alike, for meeting the huge undersupply of housing in the UK. In 2017/18, the UK provided 222,000 new houses, 2% higher than the previous year, lower than the annual average (see Figure 1). However, recent studies [1, 8-10] focused on investigating the structural, social and economic, and safety performances of MBS and found that still there are challenges associated with their use. The major reported challenges are regarding project planning, structural response/performance, fire and energy performance, transportation difficulty, reliable connection systems, lifting limit of tower cranes, lightweight and high-performance materials, lack of access during renovation and lack of design guidelines, that need to be overcome to make the MBS construction viable.

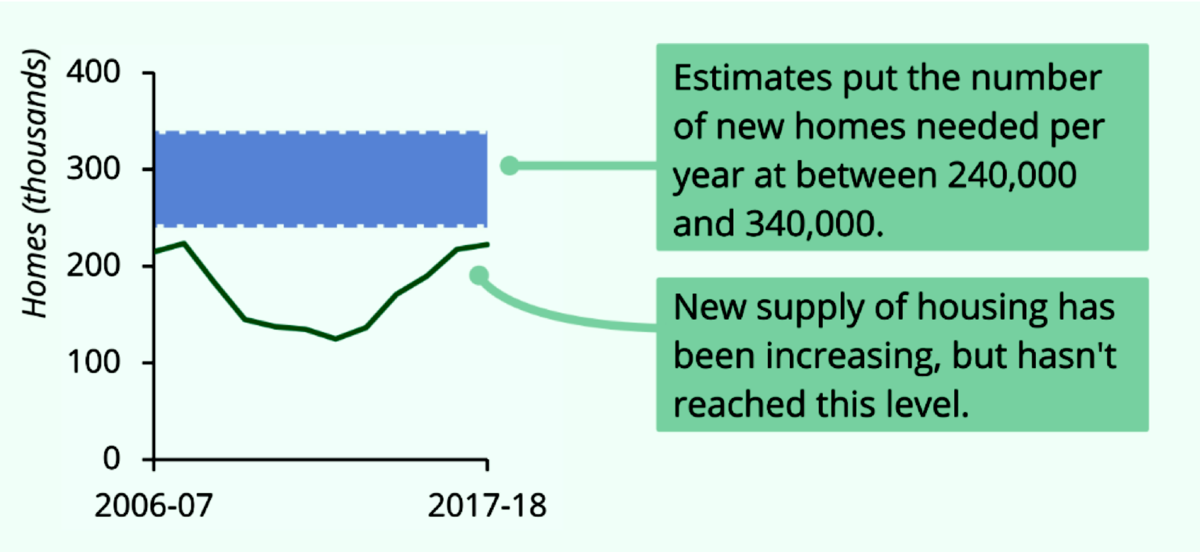


Figure 1: The housing supply in the UK recent years [5]

Most of the reported challenges can be addressed when MBS is mainly constructed with optimised CFS sections. Optimisation technique can play a vital role to meet the challenges related to MBS as it offers enhanced structural performance for a given amount of material. Moreover, material (steel) can be effectively used and the manufacturers will also experience the benefit in terms of the usage of reduced raw material. Currently available industry sections are different in dimensions when compared with a basic of the same amount of material used. This may be due to the capability of forming and press braking machines used by different manufacturers. Thus currently available industry CFS sections are likely to be inefficient in terms of structural capacity and material usage perspective. The recent sophisticated advancements in manufacturing technologies allow flexibility in manufacturing profiles. Due to these advancements, rollers used in roll-forming techniques could be adjustable to form optimised sections with different shapes and dimensions. It will lead to additional cost per meter length for innovative profiles, however, the mass production and efficient material design compensate for the additional cost.

To date, Several optimisation techniques, neural networks [11], Genetic Algorithm (GA) [12-14] and Particle Swarm Optimisation (PSO) [15-17] have been successfully employed to optimise the CFS beams. Moreover, incorporating staggered slotted perforations to the CFS channels can enhance the thermal performance of the channel [18]. However, the slotted perforations in CFS channels reduce structural performance. Incorporating slotted perforations to the optimised CFS sections and employing them into MBS would amplify the overall performance of the MBS. Limited research has been performed related to employing optimised novel CFS beams into MBS. Gatheeshgar et al. [19] introduced the concept of employing optimised hollow flange beams into MBS to enhance the structural performance of MBS and no research has been performed on employing optimised CFS beams without and with slotted perforations into MBS.

Therefore, this paper presents the concept of employing optimised CFS beams without and with slotted perforations into MBS and investigates their potential in addressing the aforementioned challenges. The novel CFS sections were optimised using PSO in order to enhance the structural performance. Then, Finite Element (FE) models were developed and validated against the experimental results. The validated FE models were used to test the performance of the optimised CFS beams. Following that a conceptual design of a module was developed using the proposed optimised innovative sections through this study. The proposed system would result in a lightweight MBS which has an ability to meet the identified challenges. The possible challenges that limit the implementation of this work could be the manufacturing of these innovative profiles and introducing staggered slotted perforations to the web. However, these could be overcome by recent advanced manufacturing technologies such as adjustable rollers in the forming process to produce different shapes and punching techniques to introduce staggered slotted perforations.

2 An overview of Modular Building System (MBS)

Off-site construction involves the planning, designing, fabricating, transporting, and assembling stages, with either all or the first three stages occurring in a factory specifically designed for this construction method. It offers a greater degree of precision and finish in less time compared to conventional construction, improves safety and resource efficiency, and can enhance build quality; providing well-suited solutions to a variety of construction projects, e.g. houses, schools, student accommodation. Figure 2 depicts how the individual completed modules are transported and assembled on-site. Lawson et al. [21] reported that even though each module needs to be transported on-site, the overall number of visits by the delivery vehicle is reduced by 70%.

(a) (b) (c)

Figure 2: Modular units (a) Transporting around the factory; (b) Transporting from the factory to onsite; (c) During onsite assembly [20]

Off-site construction can be categorised in terms of the degree of finished factory works [6, 7], as follows: 1) manufacture of components, e.g. beams, columns, off-site and assembly on-site; 2) two-dimensional panelised construction off-site and assembly on-site; 3) construction of volumetric modules without fully enclosed and finished volumetric modules without interior finishes; 4) construction of volumetric modules without fully enclosed and finished volumetric modules without exterior finishes; and 5) 95% completed volumetric modules with fixtures and finishes [7]. Figure 3 illustrates the five typologies of off-site manufacture.

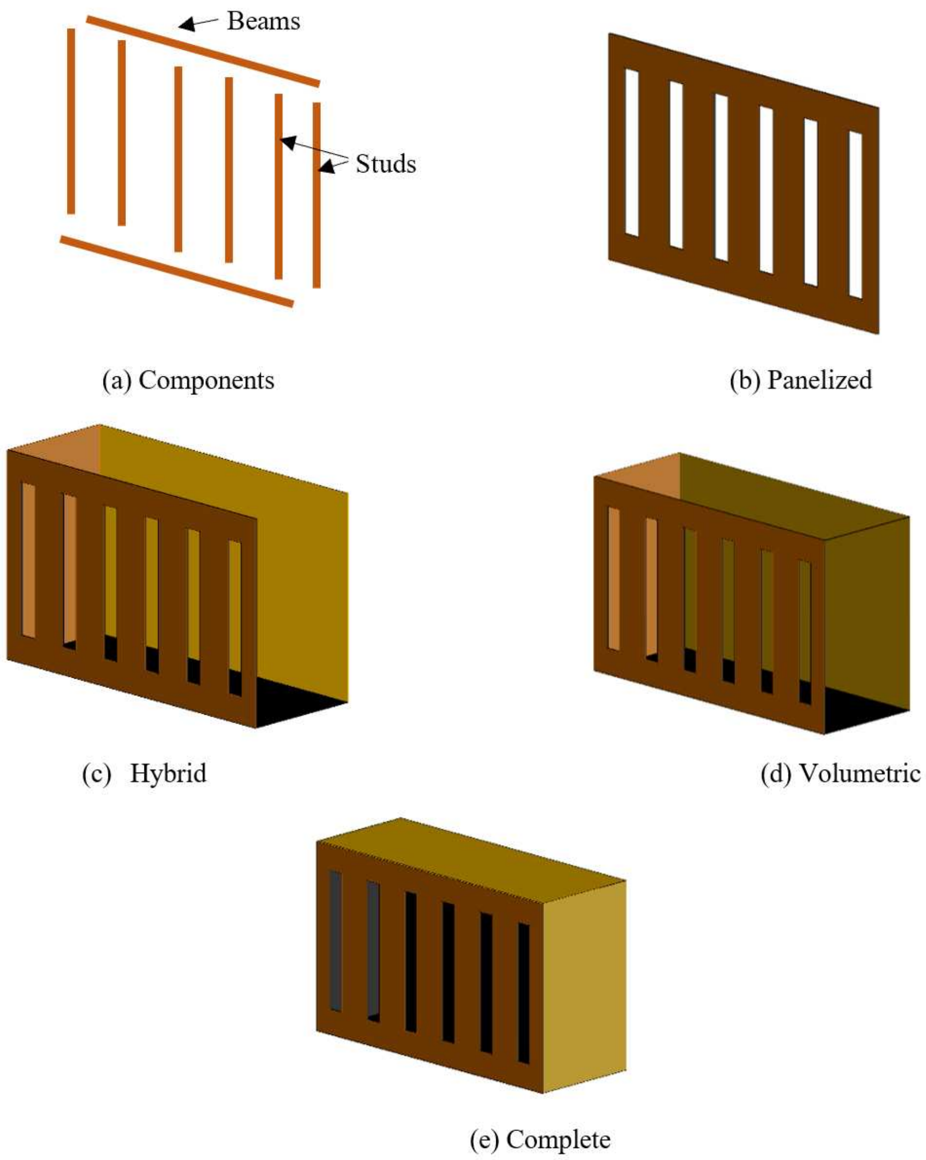


Figure 3: Typologies of off-site construction method

Volumetric modules can be further divided into two categories as load-bearing and corner supported modules in terms of structural mechanisms. Load bearing modules transfer the load through the side walls while in the corner post module, the load is transferred through corner columns from edge beams [21]. Figure 4 depicts a corner post module. In addition to that MBS is structurally strong over traditional construction. The reason for this argument is volumetric modular units are subject to the engineering process individually in an independent manner to resist the vibration during transportation and safe lifting when assembling [22].

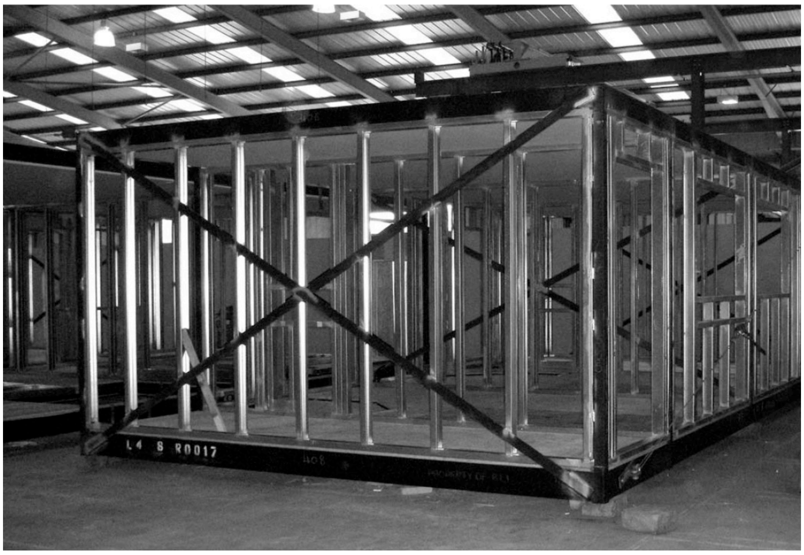


Figure 4: Corner post-module [21]

MBS can be used in a variety of building constructions, e.g. education, housing, health care, office, governments, dormitory, retail, and hospitality [23], and can be categorised in two groups in terms of usage: temporary modular and permanent modular. The temporary modular structure can be relocatable and meet short term needs, while permanent modular structures are installed and fastened to a rigid foundation due to the intention of long-lasting for several years (decades). Temporary modular structures can be particularly useful in post-disaster situations to accommodate affected people, as it can be quickly and easily dismantled and re-assembled in a new location. In general, MBS can provide more flexibility and higher efficiency compared to other methods. In regards to the latter, MBS is suggested to enhance energy performance, compared to other construction methods [24].

The energy used in buildings can be split into operational and embodied energy. Operational energy, i.e. the energy used in the form of lighting, heating/air conditioning, etc. associated with the use of the building, can be reduced with MBS due to its highly insulating and air-tight design. Lawson and Ogden [25], suggest that with modular design an energy leakage rate of less than $2m^3/m^2/hr$ can be achieved. MBS can be combined with a range of energy-efficient building practices (e.g. solar panel heating systems), and utilise building materials that meet the growing demand for environmentally friendly buildings. This is because of the embodied energy, i.e. the energy used at the extraction, processing, manufacture, and transport of building components, of buildings that are locked into their fabric as a result of the construction phase. In MBS, embodied energy is mostly contained in the materials used to manufacture the external building envelope. This energy can be preserved when buildings are repaired during their use, retaining as such their functional purpose for longer, while they can be dismantled and relocated to another site for reuse when they reach their initial end-of-use stage, extending their lifespan of the building and its modules [26]. Traditionally, when buildings were no longer needed, this energy was lost due to demolition and waste generation. With MBS, a large amount of this energy can be saved by refurbishing the modules and retaining the components with significant embodied energy. With this method, resources in the form of materials, labour, money, and time can also be conserved promoting sustainability in the construction sector.

The off-site manufacture of modules in MBS ensures that more resource-efficient construction processes occur. According to the Building Research Establishment, the UK construction industry average for material wastage on site is 13%. In comparison, site waste in modular construction is greatly reduced and all off-cuts are fully recycled in the factory [25]. With MBS design, the construction sector can gain better control of their resource efficiency, from production through to use and end-of-life management. Cost reductions both in project construction and maintenance can be achieved over the lifetime of the building, whilst providing a fast completion, on budget and to the required quality standard, reducing the risks for the client and final end-user [1]. Moreover, there are fewer vehicle movements to site, and disruption and noise levels can be reduced by 30-50% [21], compared to traditional building construction methods.

In regards to MBS using prefabricated steel modules, an Australian case study [27] showed that material consumption can be reduced up to 78% by mass compared to the use of concrete. Although prefabricated steel modules are associated with a higher embodied energy (~50%) compared to concrete modules, they present a higher potential for reuse. The study concluded that the reuse of prefabricated steel modules can save around 81% of embodied energy and 51% of materials by mass. This highlights the MBS has the potential to contribute significantly towards improving the sustainability of the construction industry.

3 Case studies on modular buildings

There are few mid-rise and high-rise modular buildings that are, or are in the process of being, completed around the world. Figure 5 shows the modular construction around the world in terms of percentage. Case studies on modular buildings generate useful information and evidence on the performance and advantages of MBS. Moreover, variety in the case studies exploring the use of MBS is necessary for developing design specifications and recommendations for modular structures at different scales and spatial context [1]. This section covers brief detail on case studies of popular modular buildings in developed countries.

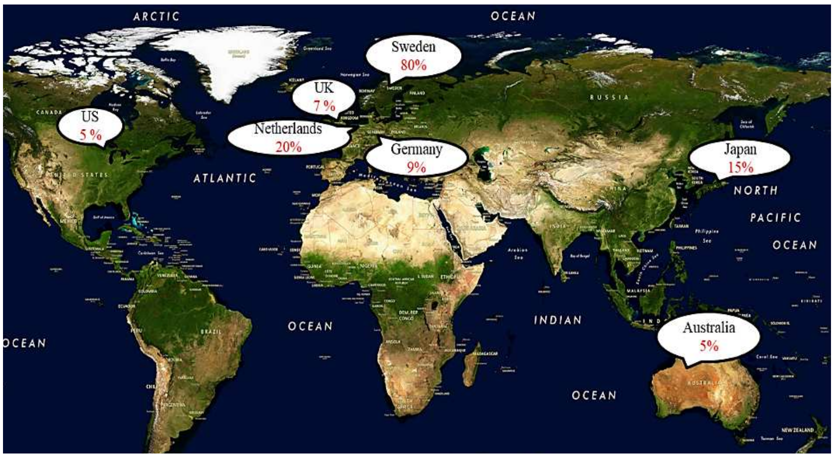


Figure 5: Modular building construction around the world

3.1 United Kingdom

Modular construction is expanding rapidly in the UK, perceived as a way to respond to three main challenges: housing crisis, skilled labour shortage, and sustainability [28]. To date, several modular buildings are being constructed and only a few of them are completed. The George Street, Croydon Towers will mark the position as the world's tallest modular building after the completion. The building is a combination of two skyscrapers, which has been forward-funded by Greystar and Henderson Park and will reach 44 and 38 storeys, respectively. The major intention of the building is to provide about 546 high-quality homes for rent, in addition, it will be utilized with winter gardens, art galleries, cafes, gyms, hubs for local business, landscaped gardens and terraces. Figure 6 depicts the architectural model and the construction phase of the Croydon building. The construction time is expected to take only two years and to be completed in 2020. Noticeably, Greystar reporting that modules are produced with 80% less waste generation compared to traditional construction [29-31]. Apex House in Wembley and Victoria Hall in Wolverhampton are the other popular modular buildings in the UK.

(a) Architectural model (b) After the completion of concrete core

Figure 6: George Street, Croydon modular towers in the UK [30, 31]

3.2 Singapore

Singapore's interest on MBS has led to many local modular construction projects predominantly focusing on reducing the construction period and labour resources [8]. Liew et al. [8] reported that Crown Plaza Hotel Extension at Changi Airport and NTU North Hill Residence Hall are the leading steel modular buildings with 10 and 13 storeys, respectively. The list of steel modular building projects completed in Singapore is provided in Table 1 while Figure 7 shows one of the steel modular buildings listed in Table 1, i.e., the Crowne Plaza Ext @ Changi Airport.

Table 1: List of steel modular buildings in Singapore [8]

Project Name	No. of storey	Function
Crowne Plaza Hotel Ext @ Changi Airport	10	Hotel
NTU Norh Hill Residence	13	Hostel
NTU Nanyang Crescent Hostel	11 & 13	Hostel
Nursing Homes (Woodlands)	9	Nursing home
JTC Space @ Tuas	9	Industrial
The Wisteria Mixed Development	12	Private residential
Brownestone Excecutive Condominium	10 & 12	Private residential
Senja Polyclinic	12	Polyclinic, nursing home

Figure 7: Crowne Plaza Hotel Ext @ Changi Airport [8]

3.3 Australia

In Australia, approximately 3-4% of the new buildings constructed annually are modular. The major limitation of this slow growth of modular construction is all the prefab constructions are expected to follow the commercial and confidential clauses [1]. However, this 3-4% of present modular construction is expected to be increased to 5-10% by 2030 [9]. Melbourne is the home of the tallest prefabricated building in Australia, the La Trobe Tower (see Figure 8(a)). It is a 44 storey modular building project completed in 2016. Another example is the Little Hero low-rise apartment in Melbourne (see Figure 8(b)). It was constructed with 58 single-storey apartment modules and 5 double-story apartment modules. This eight-story building was assembled in 8 days. Steel and concrete cores were used to withstand lateral loading [32].

(a) La Trobe tower (b) Little Hero building

Figure 8: Prefabricated modular buildings in Australia [32, 33]

3.4 China

After the establishment of the Broad Sustainable Building (BSB) in 2008, China experienced some admirable achievement in producing modular building skyscrapers within a shorter period. The construction technology of BSB is based on the 7 principles of sustainable development which include ensuring less amount of wastage generation, improved energy consumption efficiency, and producing seismic resistance buildings [2]. One pioneering achievement of this company is the construction of the Sky City. Figure 9 shows the building model of the Sky City, Changsa. This building has admirable characteristics with 838 m in vertical height and comprised of 202 floors. About 17% of the building area is utilized with commercial and spare time activity regions including offices, a hotel, 5 schools, a hospital, stores, restaurants, helipads, and basketball and tennis courts. The rest 83% is for a residential area. The noteworthy fact is that the estimated project duration is just 90 days and 95% of manufacturing work will be performed off-site [2,4].

Figure 9: Sky City modular building in China [2]

3.5 Sweden

Sweden is the leading country in the construction of prefabricated housing. More than 80% of the housing industry market is prefabricated buildings while in other developed countries including the UK, US and Australia prefabrication is less than 5% [1]. In Sweden, timber elements are mostly used in prefabricated modules. One of the typical prefabricated buildings in Sweden is shown in Figure 10. Prefabricated modules were used to develop an economical construction process. 196 prefabricated units were arranged to form 35 m high building and each module is square in shape with 3.6 m width. It has been developed to ensure well suited urban living for inhabitants [34].

Figure 10: Prefabricated modular building in Sweden [34]

4 Structural performance of optimised innovative sections

This paper also attempts to highlight the enhanced structural performance of the innovative light gauge steel sections and to increase the application into light gauge steel construction, especially in modular buildings. In this comparative study, three optimised sections are considered. It has been noticed that still, the light gauge steel construction industry highly employing Lipped Channel Sections (LCB). A commercially available LCB section is also considered as a benchmark section in order to compare the structural performance of the novel sections. In addition, the available LCB section is also optimised. Figure 11 depicts the selected benchmark section while Table 2 narrates the selected novel sections that are to be optimised to employ into MBS.

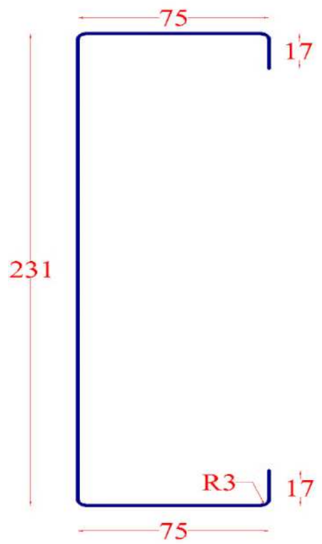
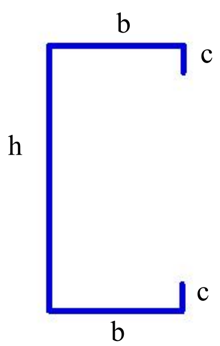
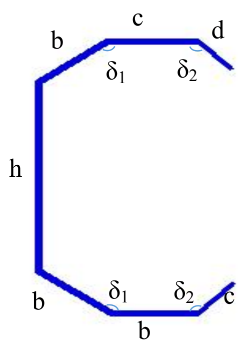
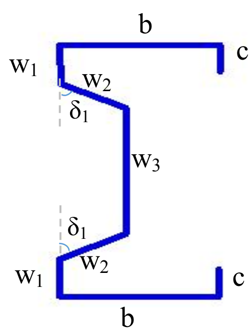


Figure 11: Benchmark LCB section

Table 2: Selected innovative sections for optimisation [17]

LCB	Folded-Flange	Super-Sigma
		

4.1 Overview of the optimisation process

The optimisation process leads to the enhanced structural performance of the selected innovative prototypes. The optimisation process was performed with PSO algorithm, which is developed based on the natural swarming behaviour of birds flock and schools of fish [35]. Moreover, PSO has some similarities and dissimilarities over GA which is previously used for structural optimisations. One of the major advantages of PSO over GA is the practical manufacturing and theoretical constraints can be incorporated easily [15]. The extensive detail on optimising structural beam members using PSO can be found elsewhere [15-17]. Initially, for the selected innovative sections, section moment capacity equations were developed based on the provisions provided in Eurocode (EN-1993-1-3 [36] and EN-1993-1-5 [37]). Subsequently, the developed section moment capacity equations were combined with the PSO algorithm which was generated through MATLAB [38]. More importantly, the theoretical constraints, that are mentioned in EN-1993-1-3 [36] and practical and manufacturing constraints reported in [16], were set as the lower and upper bounds of the varying parameters (see Table 2). During the optimisation process, the amount of material was maintained as same for the benchmark section (Coil length = 415 mm and Thickness = 1.5 mm). Further, the similar mechanical properties were also used for the benchmark and selected innovative sections (Modulus of elasticity = 210 000 MPa, Yield strength = 450 MPa and Poisson's ratio = 0.3). The optimised dimensions for the selected innovative sections and the optimised section moment capacities are given in Table 3. The optimised section moment capacities were then verified with the advanced FE analysis.

Table 3: Optimised capacities of the selected sections with dimensions [17]

Prototypes	h (mm)	b (mm)	c (mm)	d (mm)	w_1 (mm)	w_2 (mm)	w_3 (mm)	δ_1 (°)	δ_2 (°)	Capacity (kNm)
LCB_benchmark*	231	75	17	-	-	-	-	-	-	10.30
LCB_optimised	269	50	23	-	-	-	-	-	-	13.38
Folded-Flange	185	48	50	17	-	-	-	105	95	16.12
Super-Sigma		50	17.5	-	41	30	139	34	-	17.43

*Dimensions given for LCB benchmark is not the optimised dimensions

4.2 Analysis overview

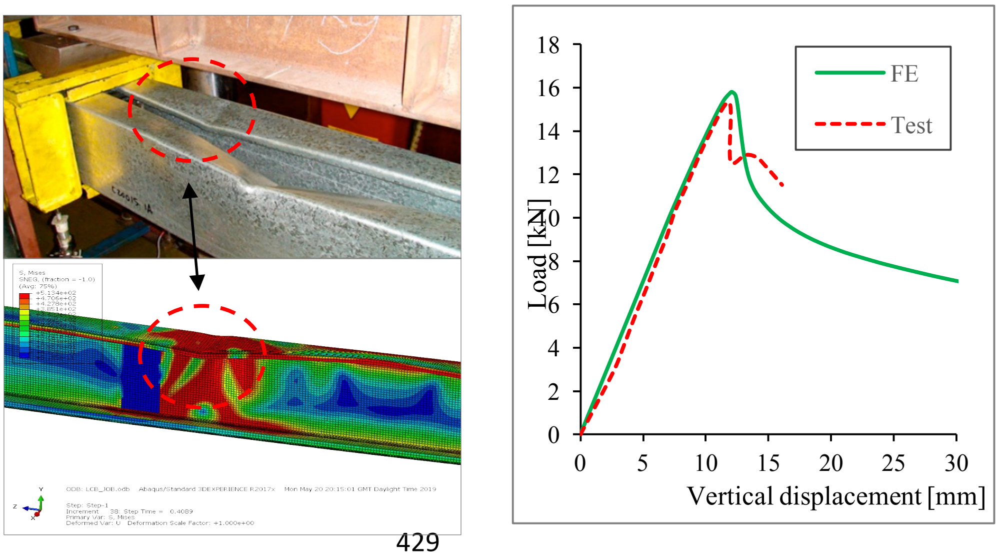
The optimised novel sections were analysed with an advanced FE method in order to investigate the flexural behaviour extensively. A general-purpose software, ABAQUS version 2017 [39], was used for this investigation. FE models of four selected prototypes were modelled as four-point loading set-up with simply supported boundary conditions. This four-point loading arrangement ensures pure bending failure in the mid-span with the absence of shear stress. A detailed description of the FE model development including element type, material properties, mesh refinement, load and boundary conditions, geometric imperfections, and analysis method are provided in Table 4.

Table 4: FE Model description and analysis method

Model characteristics	Brief description
Model set-up	Four-point loading with middle span and two adjacent spans.
Boundary conditions	General simply supported boundary conditions
Loading method	Displacement control loading with smooth step amplitude at two middle supports, displacement was set to increase from 0 to 70 mm.
Residual stress	Residual stress is not incorporated into the model as Keerthan and Mahendran [40] reported that the effect of residual stress in CFS beams is less than 1%.
Material model	CFS was assumed as having perfect plasticity behaviour. The research findings from Keerthan and Mahendran [40] showed that adopting strain hardening behaviour only improve the capacity by 1%. Therefore, strain hardening behaviour was not considered in FE analyses.
Element type	Beam model was developed with S4R shell element available in ABAQUS. Shell element has the ability of simulating non-linear behaviour during the ultimate bending behaviour analyses. S4R shell element has the reduced integrations, thus less time consuming for the analysis than S4 shell elements in ABAQUS [41].
Mesh refinement	Web and flange segments were provided with a mesh refinement of 5 mm × 5 mm while the folded edges (corners) were provided with finer mesh refinement of 1 mm × 5 mm due to the critical behaviour of bends on the capacity. For slotted channels, the web was provided with a mesh refinement of 1.5 mm × 5 mm.
Geometric imperfections	The magnitude of the imperfection was considered as a function of plate segment width, d_1. The magnitude of $0.006d_1$ was assigned to all FE models via bifurcation buckling analysis [42]. The shape of the imperfection was introduced via *IMPERFECTION option available in ABAQUS.
Web side plates	Web side plates were simulated with coupling constrain and with a reference point (shear centre). The web side plate area in the model was coupled to the shear centre and loading and support boundary conditions were applied to that point [43].
Analysis method	Linear buckling analysis – First elastic buckling mode, which is commonly a critical mode, was used to incorporate the imperfection shape and magnitude Non-linear static analysis – The effect of material yielding and large deformations were taken into account
Convergence criteria	Convergence difficulty was overcome by specifying artificial damping factors. The default artificial damping factor defined in ABAQUS was employed.

4.3 Validation

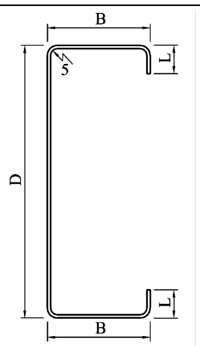
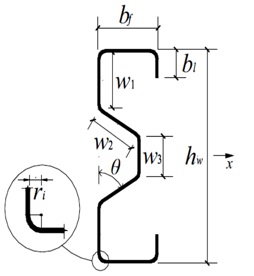
The FE models were developed based on the validation of experimental data in order to ensure the FE model characteristics are well suited to predict the ultimate bending capacity accurately. With the mentioned model characteristics FE models of LCBs and Sigma sections were developed, subsequently, the failure modes and ultimate section moment capacities were verified with the experimental results reported by Pham and Hancock[44] and Wang and Young [43], respectively. It is noteworthy to mention that for both LCB and Sigma sections validation process, Web Side Plates (WSPs) were simulated with coupling constraint which restrains the all the translation and rotation of the WSP surface in the model to a single point (shear center) as used in [43]. Table 5 provides the validation results of the LCB and Sigma sections with experimental data. Overall, the mean value of the test to FE analysis is 0.96 while the corresponding coefficient of variation (COV) is 0.059. Figure 12 shows the load-displacement behaviour and failure mode comparison of FE results over experiment results of the C20015 LCB section. Based on these comparisons, it can be concluded that FE analysis reveals a satisfactory agreement with experimental results. Therefore, considered FE characteristics are able to predict the ultimate bending capacity accurately of the optimised novel sections.



(a) Failure mode comparison (b) Load- vertical displacement comparison

Figure 12: Comparison of failure mode and load- vertical displacement behaviour for C20015 [45] with FE results

Table 5: Validation of the bending models with experimental data

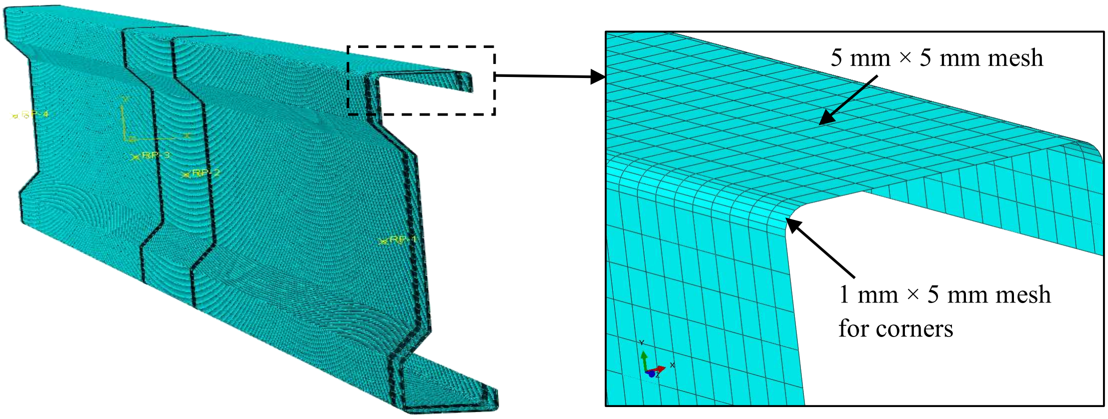
Specimen		M_{Test} (kNm)	M_{FEA} (kNm)	M_{Test}/M_{FEA}
Pham and Hancock [44] – LCB sections				
	Mw C15015	9.47	9.62	0.98
	Mw C15019	12.90	14.72	0.88
	Mw C15024	17.96	17.05	1.05
	Mw C20015	12.20	12.69	0.96
	Mw C20024	27.88	27.53	1.01
Wang and Young [43] – Sigma sections				
	C-0.48-B4	1.03	1.07	0.96
	C-1.0-B4	2.99	3.31	0.90
	Min			0.88
	Max			1.05
	Mean			0.96
	COV			0.059

4.4 Flexural performance of optimised sections

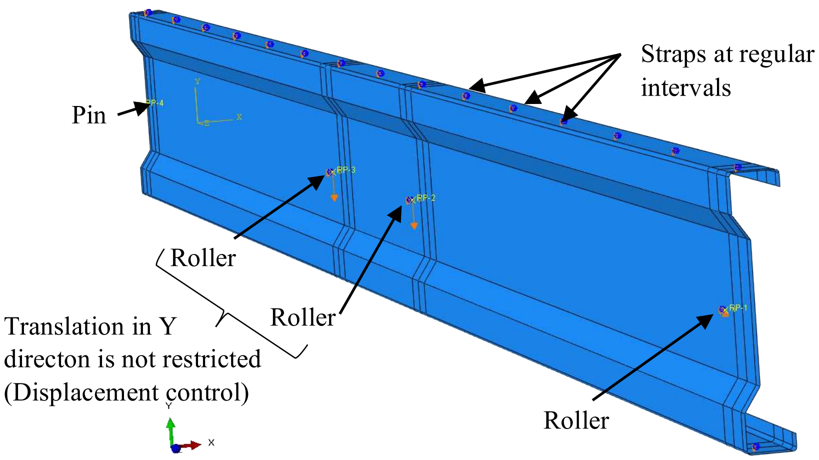
The selected innovative sections were modelled and analysed through FE analysis based on the validation process. Similar model characteristics were adopted to investigate the flexural behaviour of the innovative sections. Figure 13 shows the developed FE model of the optimised sigma (Super-Sigma) section. This figure illustrates the provided mesh refinement and the details of the simply supported boundary conditions. Other considered innovative sections were also provided with similar boundary conditions. Figure 14 shows the flexural failure modes observed from the FE analysis and as expected the failure occurred within the pure bending zone (middle span). The load -vertical displacement (displacement of the midpoint of the span) relationships of the considered sections are plotted in Figure 15. Further, the stage by stage failure mode for the Super-Sigma section is narrated in Figure 16. The section moment capacities obtained for the considered innovative sections through FE analysis were then compared with the section moment capacity predictions obtained from the EN 1993-1-3 [36]. Table 6 provides the comparison of the section moment capacity predictions from FE analysis and EN 1993-1-3 [36]. The result gives a mean value of 1.00 along with a COV value of 0.022. Thus, FE and EN 1993-1-3 [36] prediction show a good agreement on predicting section moment capacities. Moreover, Table 6 also provides the bending capacity enhancement of the optimised innovative CFS sections in terms of percentage by taking the selected commercially available conventional LCB (see Figure 11) as a benchmark.

Table 6: Comparison of section moment capacity predictions obtained from EN 1993-1-3 and FE analysis [17]

Sections	M_{EC3} (kNm)	M_{EC3} (%)	M_{FE} (kNm)	M_{FE} (%)	M_{EC3}/ M_{FE}
LCB_benchmark	10.30	100 %	10.41	100 %	0.99
LCB_optimised	13.38	130 %	13.28	128 %	1.01
Folded-Flange	16.12	156 %	16.60	159 %	0.97
Super-Sigma	17.43	169 %	16.90	162 %	1.03
Min					0.97
Max					1.03
Mean					1.00
COV					0.022

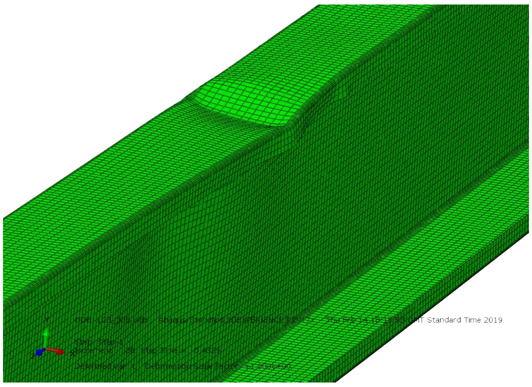


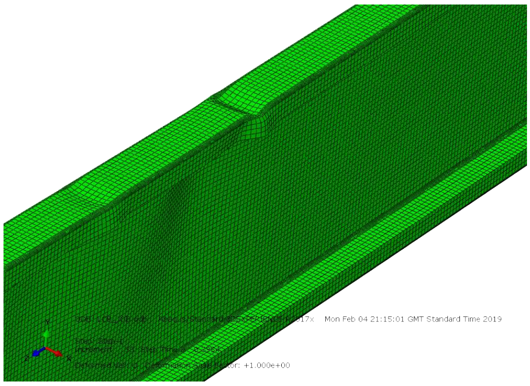
(a) FE discretization



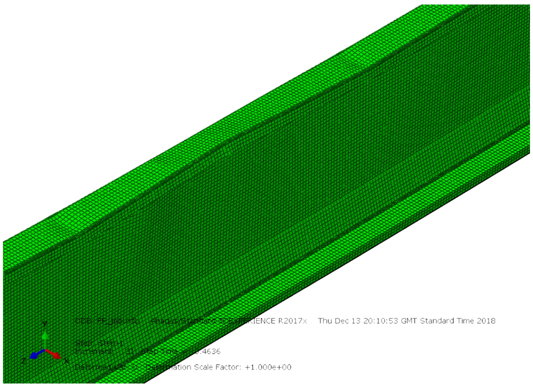
(b) Boundary conditions

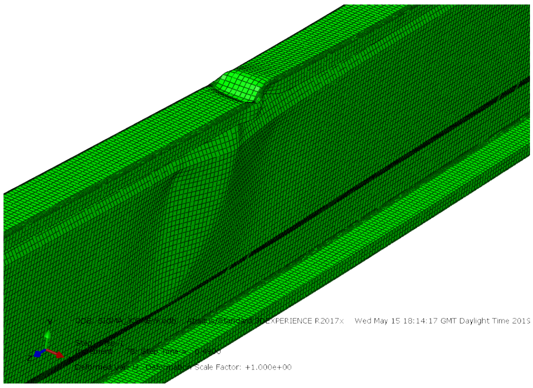
Figure 13: FE model development of Super-Sigma section





(a) LCB benchmark (b) LCB optimised





(b) Folded-Flange (b) Super-Sigma

Figure 14: Flexural failure modes of considered innovative sections

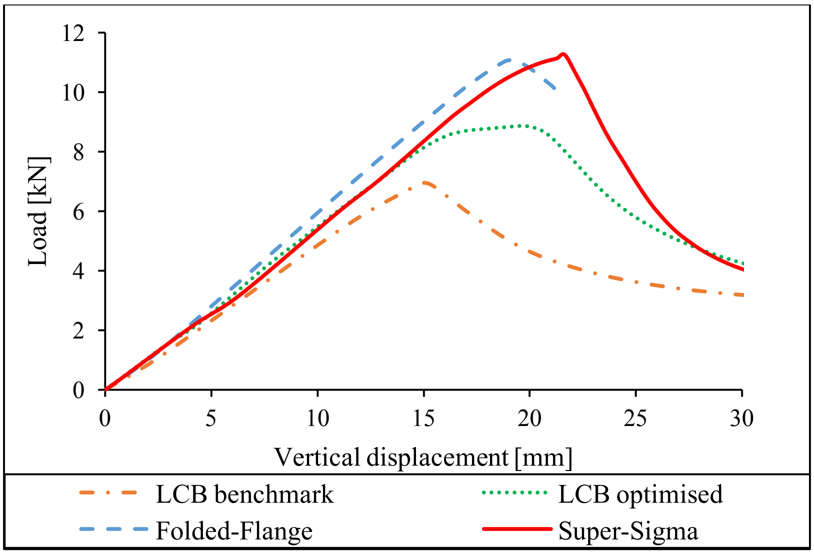
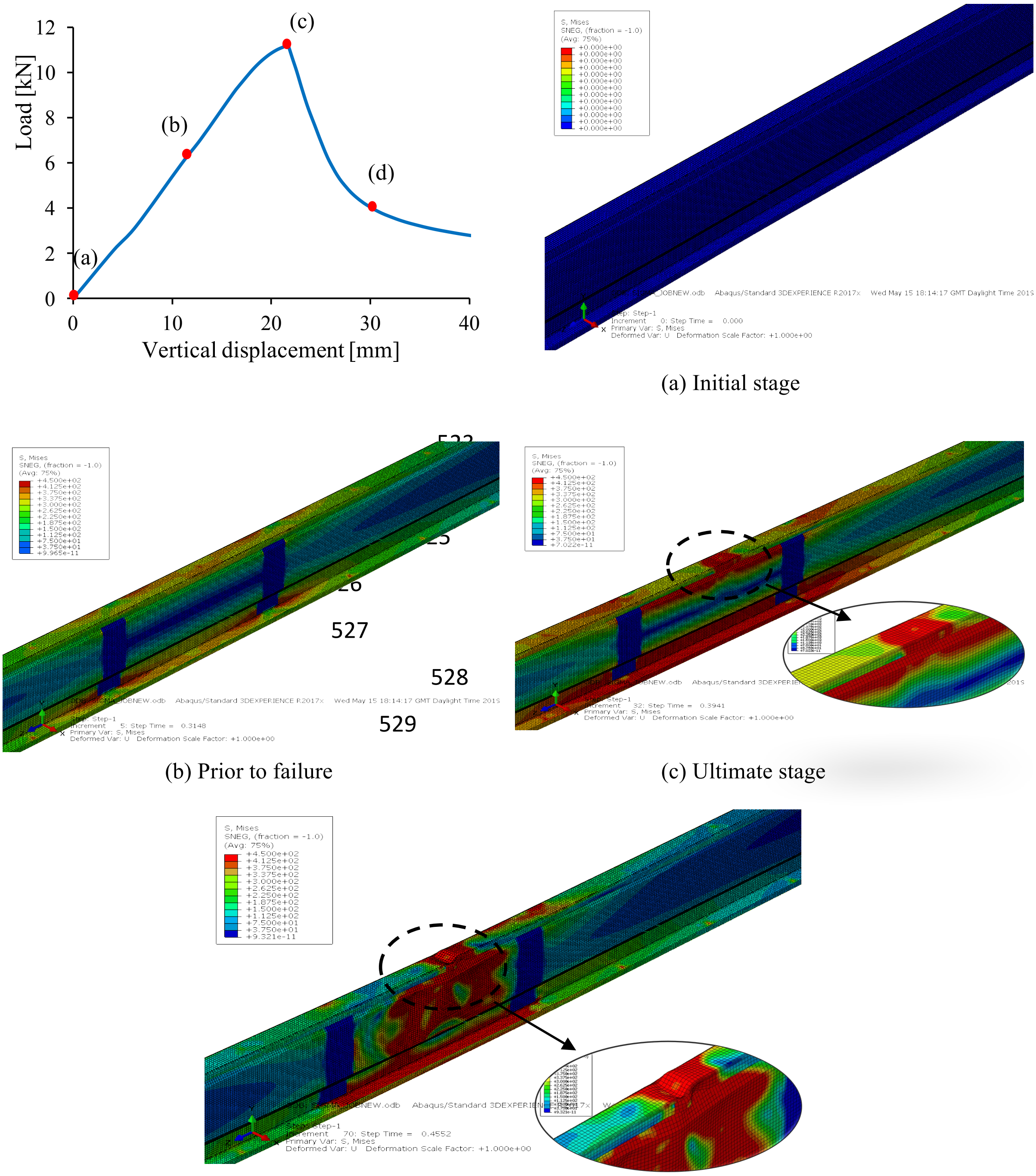


Figure 15: Load – vertical displacement behaviour of innovative sections



(a) Initial stage

(b) Prior to failure

(c) Ultimate stage

(d) Post failure

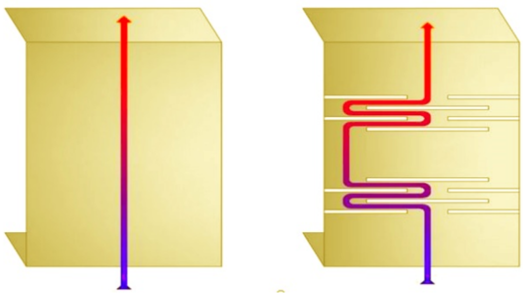
Figure 16: Failure modes of Super-Sigma section at different stages

The results reveal that Super-Sigma section has the ability to withstand about 65% higher bending actions compared to the benchmark section. When compared to other considered sections (lipped channel section and folded-flange sections) with the same amount of material, the super sigma section has the highest bending capacity. Moreover, sigma sections naturally have a closer shear centre to the web due to the stiffened web. Therefore, this adds more value to the Super-Sigma sections because the closer shear centre to the web minimises the torsional failure due to eccentric loading. In common practice, substantial lateral restrain methods are being used to overcome this torsional issue. Therefore, employing Super-Sigma section as flexural members in floor and roof panels would result in a substantially improved structural performance along with the lightweight structural system.

4.5 Flexural performance of slotted sections

Incorporating slotted perforations to CFS channels will enhance the thermal performance as it increases the thermal transmittance path (see Figure 17). However, these slotted perforations can reduce the load carrying capacity of the CFS channels. Therefore, slotted perforations were provided to webs of the optimised sections while the reductions of bending capacity were also evaluated through FE analysis. The dimension of the slots and its configuration in the web is depicted in Figure 18. Model characteristics provided in Table 4 were used to construct and analyse the slotted channels. Figure 19 illustrates the failure mode obtained for the optimised sections with the incorporation of slots while Figure 20 shows the reduction of bending capacity due to the incorporation of slots. It can be noticed that for all the sections less than 10% of the bending capacity is reduced and these reductions are well ahead of the bending capacity of the benchmark section. To elaborate, 18%, 55%, and 57% of flexural capacity enhancements were achieved for optimised LCB, folded flange, and super-sigma sections, respectively even with the inclusion of slotted perforations.

(a) Application of slotted perforated CFS channels



(b) Heat transfer path of solid and slotted perforated channels

Figure 17: Slotted perforated CFS channels

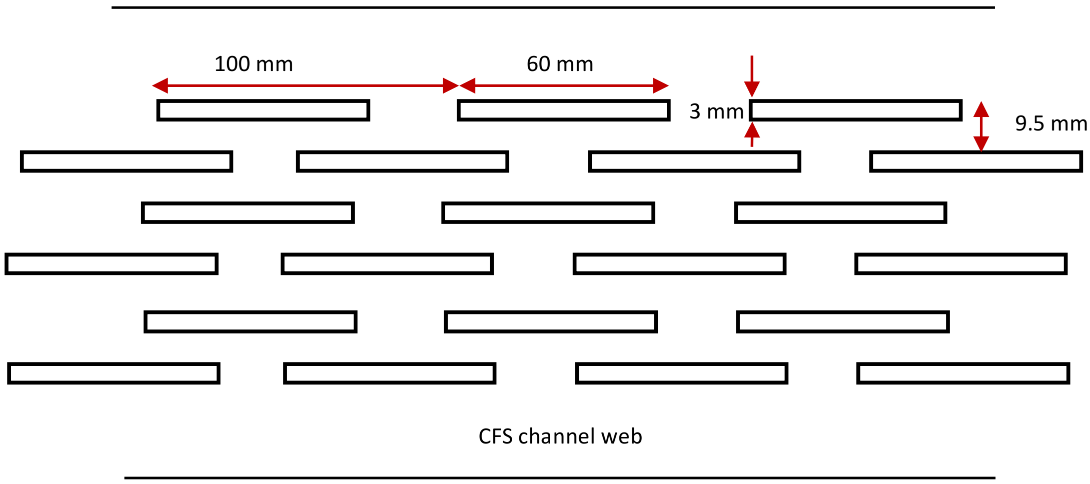
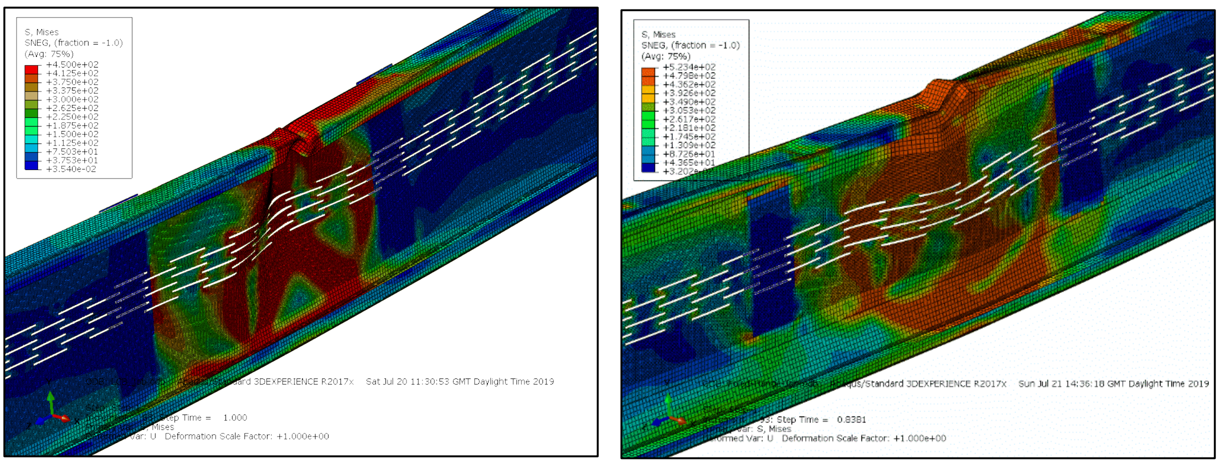
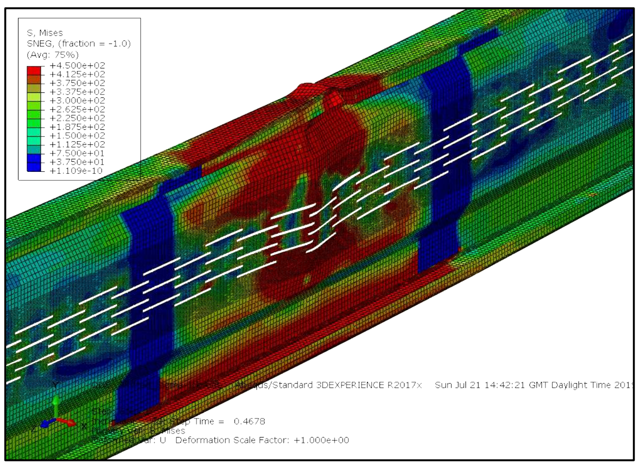


Figure 18: Slots configuration and dimensions



(a) Optimised LCB with slotted perforations (b) Folded-Flange with slotted perforations



(c) Super-Sigma with slotted perforations

Figure 19: Failure modes obtained for optimised CFS sections with slotted perforations

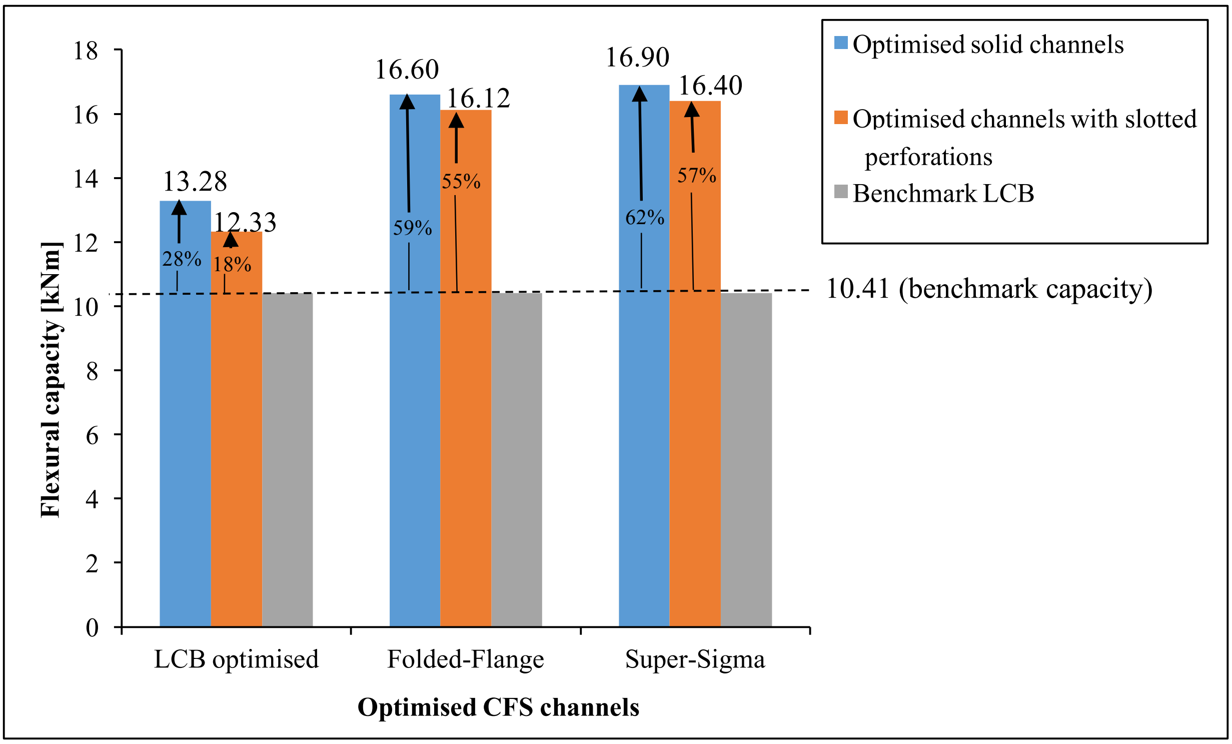


Figure 20: Bending capacities of optimised channels with slotted perforations

Therefore, including slotted perforations to the optimised sections would results in enhanced bending capacity along with amplified thermal performance. These findings are significant enough to address the challenges related to modular buildings. The detail on how these optimised CFS channels with slotted perforations can address the MBS challenges are described in following sections.

5 MBS challenges and solutions

5.1 Structural efficiency

MBS can be identified as a complex structural system despite its easy installation process. The load transferring mechanism in MBS cannot be easily understood [1] as these systems use non-conventional connections which can be classified as inter-module connection, intra-module connection, and module to foundation connection. In addition, Navaratnam et al. [1] state that there is limited research to study the structural response of MBS. Therefore, components with enhanced load carrying capacity are recommended to overcome the complexity in load transferring mechanism and to ensure a safe design in extreme load scenarios. The optimised sections are suitable to meet this challenge as those have up to 65% of flexural capacity enhancement.

5.2 Fire resistance and energy performance

Nowadays more attention is paid towards fire safety of building after the detrimental fire accident occurred at Grenfell Tower, London, UK in 2017. Recent research studies [1, 8, 10] highlighted that there are limited studies related to fire performance of MBS. The fire safety of modular buildings can be divided into two categories: local fire safety and global fire safety. The first one defines the fire resistance of individual module and the latter one is about preventing the fire spread from module to module [8]. Webs in CFS in beams are often exposed to fire and temperature rise in webs occurs at a higher rate than flanges, especially when flanges are attached to the floor toppings. This rapid temperature rise can be controlled by providing staggered slotted perforations in CFS beam web and that will result in improved fire performance [46]. Providing slotted perforations to the optimised CFS sections as proposed through this study enhances the response to changes in temperature that could ultimately improve the energy efficiency of the MBS.

5.3 Lightweight materials

Lacey et al. [10] and Liew et al. [8] highlighted the need for a lightweight structural system with high-performance materials for MBS. CFS modules are preferred over concrete modules as steel modules are 20-35% lighter than concrete modules. MBS entirely employed with light gauge steel members can reduce the construction time compared to concrete modules, and promote great flexibility. Concrete joints can only be connected with in-situ grouting, while steel connections can be simply joined together with bolts [8]. Moreover, CFS components can be replaced, easily reassembled, and have no long-term issues such as durability, creep, and shrinkage.

Table 7 shows the entire weight distribution of a steel modular unit. About 40% of a modular unit's weight is attributed to the partition wall panels, while floor slab panels claim about 30% [8]. The optimised CFS sections always lead to material saving compare to conventional CFS sections. Replacing the floor slab with optimised light gauge steel floor panel employed with folded-flange and super-sigma sections will substantially reduce the weight of the modular unit.

Table 7: Weight distribution of a steel modular unit [8]

Module components	Weight distribution
Partition	40%
Floor slab	30%
Finishes	14%
Ceiling deck	7%
Column	6%
Beam	3%

5.4 Access requirements

Ferdous et al. [9] and Lacey et al. [10] reported that workers face accessibility limitations to install inter-module connections. This may be due to the complex arrangement of the MBS elements. The optimised light gauge steel members proposed in this study have enhanced load-bearing capacities. Those members can carry the loads from a large area, therefore, it results in the enhanced spacing between the members. For example, a spacing of 400 mm is generally provided between conventional floor joist members and this system could be replaced with folded-flange or super-sigma floor joist with 600 mm spacing. This enhanced spacing between the members and that would address the problem of the limited access in modular buildings for the workers to access the inter-module connections and even during repairing/replacing structural members.

5.5 Transportation limitations

Modular construction involves a phase of transporting modules from off-site to on-sites via trucks. Generally, the weight of a steel modular unit lies around 20 t [8]. It should be noted that certain roads and bridges have weight limitations and there are some weak bridges with weight limits below 20 t. In this situation, an alternative route is required to transport the modules to on-site for assembly and that may cause additional expenses as well as delay in the project timeline. This challenge can be meet through employing optimised CFS sections proposed in this study into MBS as it results in lightweight modules.

5.6 Lifting capacity of tower crane

The lifting capacity of the tower crane (generally less than 20 t) has been identified as one of the major on-site issues in MBS through the research study performed by Liew et al. [8].

Further, that study claims 60% cost increment for tower crane when lifting weight is beyond 20 t. The use of optimised CFS sections in MBS can significantly solve this issue as it ensures a lightweight module as explained in section 5.3.

Therefore, utilizing MBS with optimised Super-Sigma sections will able to meet the identified challenges of the need for improved structural, fire and energy performances, lightweight structure, access difficulties during the repair, transportation difficulties and weight limits of the tower cranes to lift a module. Moreover, these optimised Super-Sigma sections can be employed as purlins and rafters in light gauge steel constructions.

6 Design of MBS using optimised sections

6.1 A brief summary of design of light steel modules

This section summarises the structural design procedures for light steel modules given by Lawson et al. [47]. Modules are generally designed according to the standard specifications of a particular project. The structural design of light gauge steel modules in accordance with UK National annex and Eurocodes pays attention to several key factors. Those are load and load combinations, types of the modules to be used, the connection between modules, stability methods (bracing, diaphragm action, moment-resisting connections), construction tolerances, individual design of structural elements, and structural integrity. Table 8 presents the design checks to be ensured for light gauge steel modules. These design guidelines approximate the design of MBS even though there are no specific standards or recommendations for modular building design.

6.2 Conceptual design of MBS using optimised CFS sections

This study has identified that the Super-Sigma sections have enhanced flexural performance than conventional sections. Therefore, employing Super-Sigma sections into MBS as flexural members will result in a more economical and efficient design solution. Lawson [48] illustrated the arrangements of the structural elements in a corner post-module constructed with LCB sections (see Figure 21). Since Super-Sigma sections have been identified as better performance over LCB in terms of flexural capacity, proposed MBS will be designed with Super-Sigma sections (ceiling and floor joists). The loads from the Super-Sigma floor and ceiling joist will be transferred to longitudinal edge beams which are connected to the corner posts (see Figure 22).

Table 8: Design checks for light gauge steel modules [47]

Checks	Equations	Notations
Permitted cumulative out of –verticality tolerance	$\delta_H = 12(n-1)^{0.5}$	n = number of modules in the vertical assembly
Additional moment generated on the base module (due to combined effect of eccentricities of loading and installation)	$M_{add} = P_{wall}\Delta_{eff}$ $\Delta_{eff} = 3n^{1.5} \ \ for \ \ n < 12$	P_{wall}= Compression force at the base Δ_{eff}= effective eccentricity of the vertical group of modules
Effective slenderness of wall studs	$\lambda = {l_{eff}}/{r_{yy}}$	l_{eff}= effective length of the stud r_{yy} = radius of gyration about the major axis
Buckling reduction factor for studs	$x = \frac{1}{\emptyset + \sqrt{\emptyset^2 - \bar{\lambda}^2}}$ $\bar{\lambda} = \frac{\lambda}{\pi}\sqrt{\frac{f_y}{E}}$ $\emptyset = 0.5\left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \lambda^2\right]$	$\bar{\lambda}$= slenderness ratio f_y= yield strength of the steel E= Modulus of elasticity
Compression resistance of the member	$P_c = A_{eff} x f_y$	A_{eff}= Effective area of the cross-section
Combined bending and compression	$\frac{P}{P_c} + \frac{P_e + M_w}{M_{el}} \leq 1.0$	P= Applied compression force M_w= Bending moment due to wind loading M_{el}= Elastic bending resistance
Bending of horizontal member	$M \leq M_{el}$	M= Applied bending moment
Serviceability limits	Imposed loads deflections ≤ span / 450 Total load deflection ≤ span / 350 but ≤ 15 mm Natural frequency ≥ 8 Hz for rooms ≥ 10 Hz for corridors	
Natural frequency of floor	$f = \frac{18}{\sqrt{\delta_{sw}}}$	δ_{sw}= deflection due to the self-weight of the floor and an additional load of 30 kg/m^2
Combined compression and bending actions on corner posts	$\frac{P}{P_c} + \frac{P_e + M_W}{M_{by}} + \frac{Pe}{M_{bz}} \leq 1.0$	M_{by}= Buckling resistance moment in y direction M_{bz}= Buckling resistance moment in z direction e= Total eccentricity of axial load

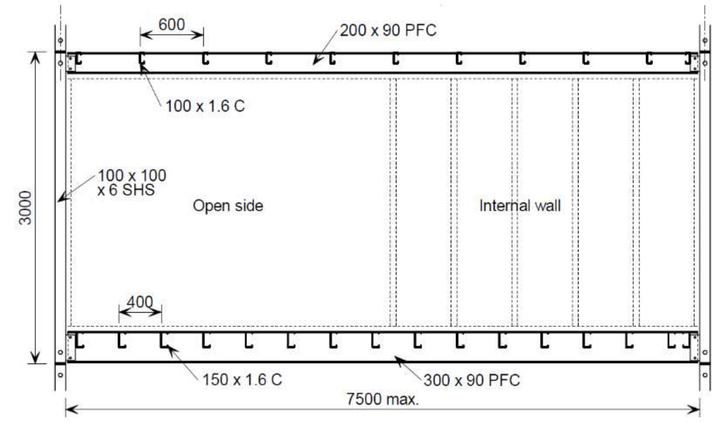


Figure 21: Common structural member arrangement of a corner post module [48]

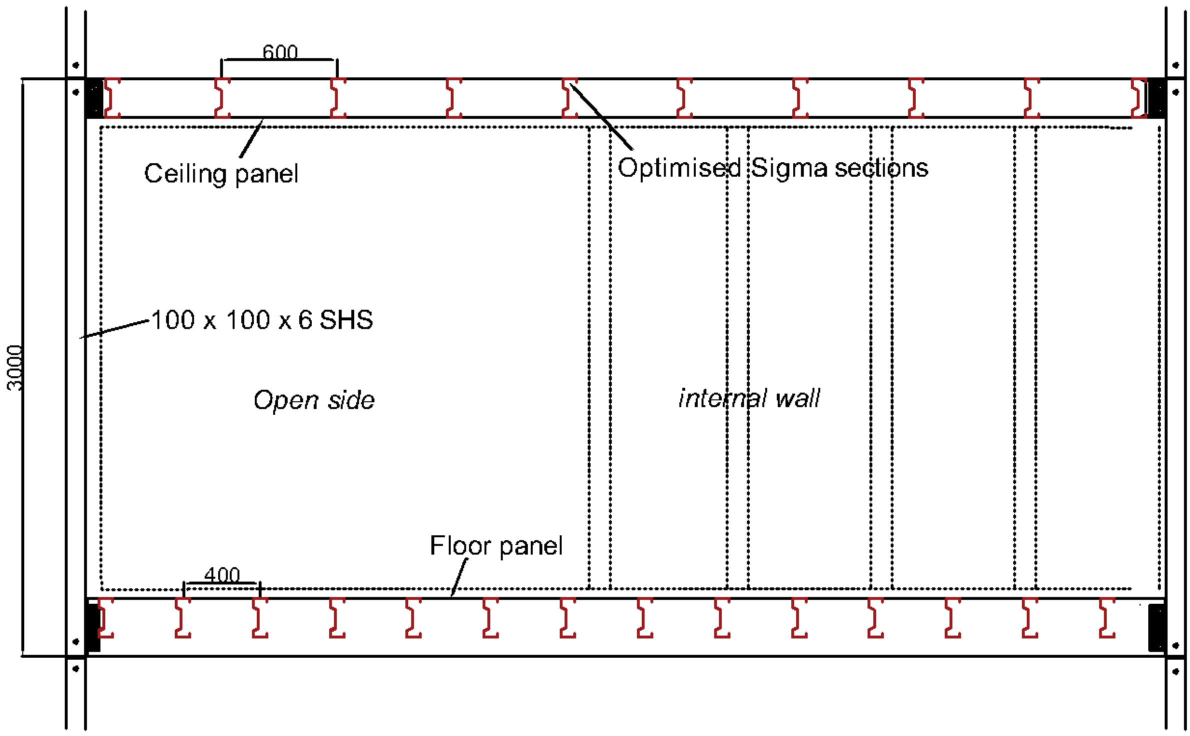


Figure 22: Conceptual layout of the corner post module employed with Super-Sigma sections

The proposed framework of the module is employing CFS members, such as Square Hollow Section (SHS) columns and either high gauge CFS or hot rolled steel edge beams that are bolted together. The stability of the building generally depends on a separate bracing system in the form of X-bracing in the separating walls. For this reason, proposed fully open-ended modules be not used for buildings more than three storey high. Where used, infill walls and partitions within the modules are non-load bearings, except where walls connected to the columns provide in-plane bracing. As recommended by Liew et al. [8], SHS column can be filled with lightweight concrete to maintain the stability for medium and high rise MBS. The corner posts provide the compression resistance and are typically 100 x 100 SHS members. The edge beams will be connected to SHS posts by fin plates, which provide nominal bending resistance. End plates and bolts to the SHS members will also be used as shown in Figure 23.

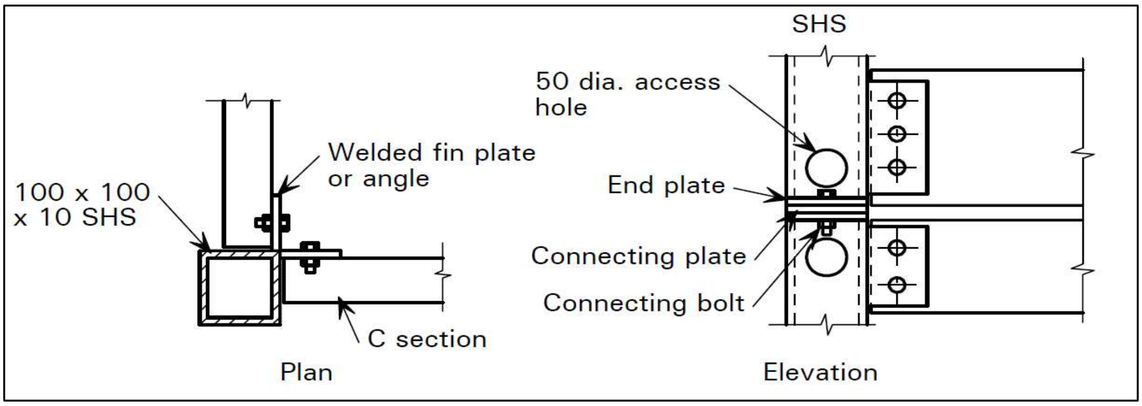


Figure 23: Corner post module connection [48]

Further research on modular building connections, structural tests and advanced finite element models of modular building systems are in progress. It should be noted that the spacing between floor/ceiling joists can be increased for Super-Sigma sections compared to LCB sections as Super-Sigma sections can bear about 65% higher flexural capacity than the conventional LCB sections.

7 Ongoing and Future works

This paper introduces the concept of employing optimised innovative CFS section into MBS to enhance the structural performance and ensuring the lightweight module. In addition to the newly proposed Super-Sigma and other sections, few other innovative CFS are also under consideration (see Figure 24). The authors of this paper are actively working on optimising these sections by considering the section moment capacities. Moreover, as shown in Figure 25 and Figure 26, authors are also involving in studies of analysing full-scale floor panel, full-scale corner post module, full-scale mid-rise, and high-rise modular buildings through advanced FE method and structural tests. The current stage involves developing full-scale FE models to investigate the global behaviour of modular buildings rather than component base investigations. All the inter-module connections, intra-module connections, and module to foundation connections are necessary to be incorporated into full-scale FE models, which will be a challenging task.

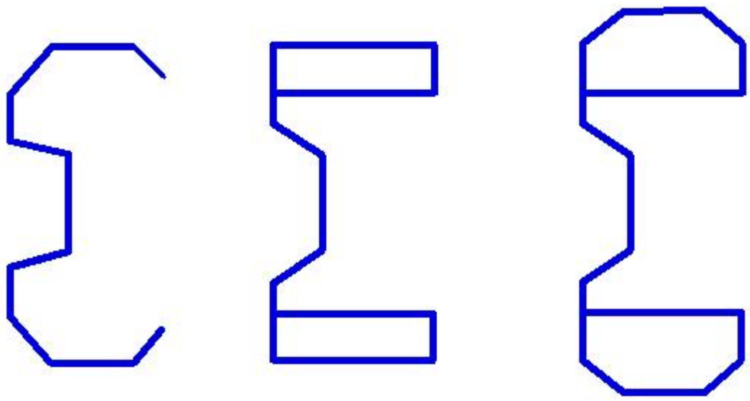
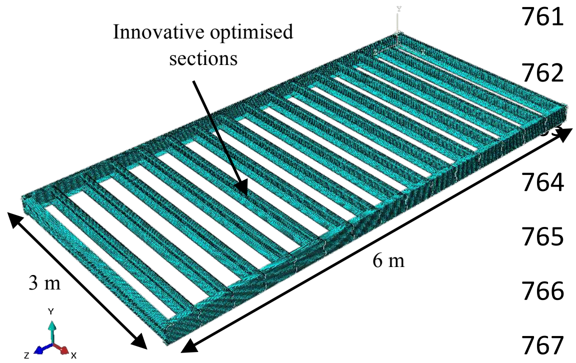
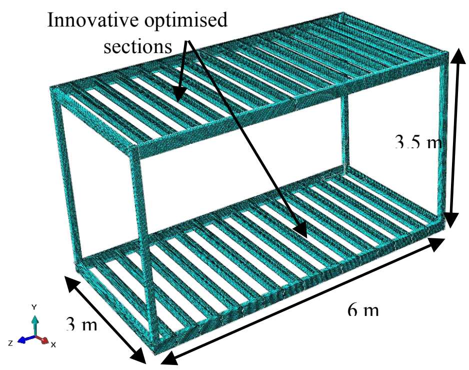


Figure 24: Innovative CFS sections under consideration



(a) Floor panel



(b) A corner post module

(c) 2 storey modular building

Figure 25: FE model development of MBS using optimised innovative sections

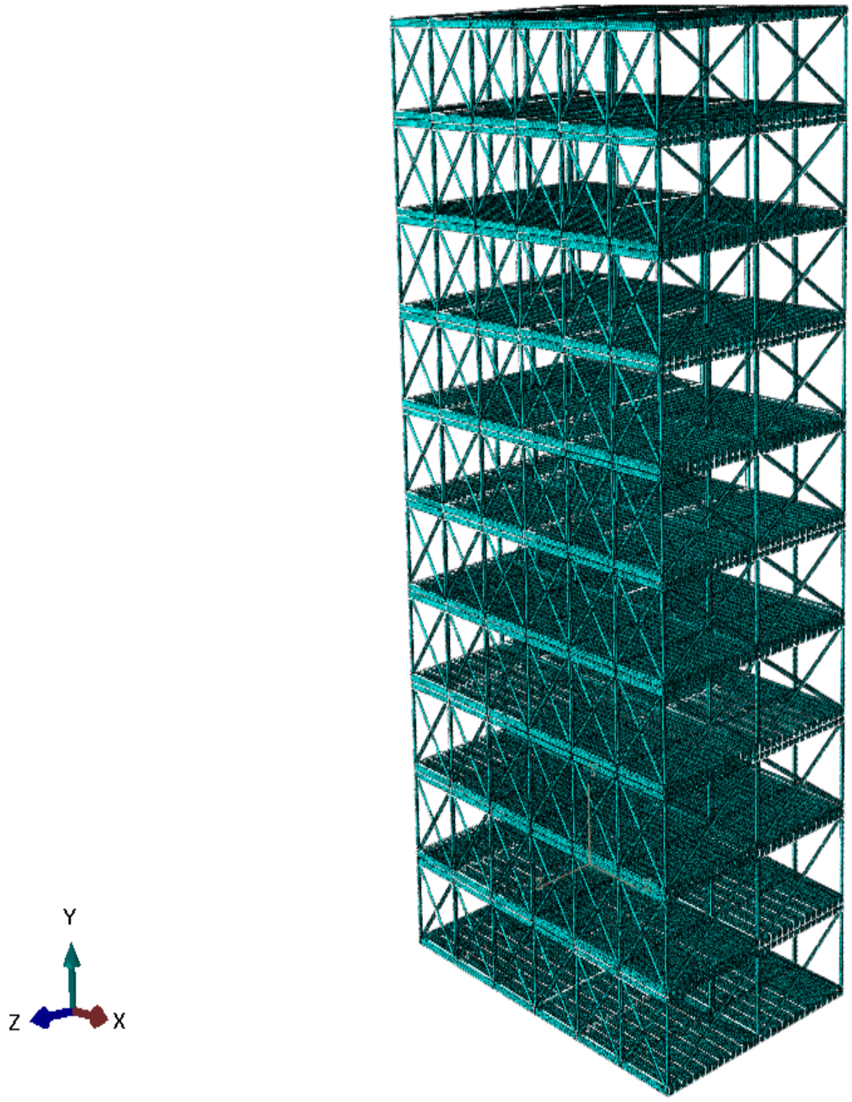


Figure 26: Full scale FE model development of high rise modular building supported with bracings

8 Concluding remarks

The construction industries in the UK are unable to meet the present housing crisis. MBS has the potential to solve the housing crisis owing to its high productivity, enhanced structural performance and shorter construction period. Wider benefits associated with cost reductions, reduce risk of delivery on time and budget, and improved resource efficiency in terms of materials and energy used can also be delivered with the use of MBS, raising its potential market penetration in the future. This research proposes to employ the optimised CFS sections with and without slotted perforations into MBS to improve structural, fire, and energy performances. The optimisation of novel sections using PSO revealed an enhanced flexural capacity of approximately 30%, 60% and 65 % for LCB optimised, Folded-Flange and Super-Sigma sections, respectively. These capacities were verified with FE analyses. It is highly recommended to employ the Super-Sigma sections into MBS as it claims the dual advantage of enhanced structural performance (65% for solid web and 57% for slotted perforated web) and closer shear centre to the outer web. The latter will result in less need of additional lateral restrains in order to prevent the twisting effect. Further, it was found that incorporating optimised sections with slotted perforations into MBS is able to meet the recently identified challenges through recent research studies. Such optimised novel CFS sections are, therefore, proposed to be used in light gauge steel frameworks and modular building systems in order to enhance the structural, fire, and energy performances.

Acknowledgements

The authors of this paper would like to acknowledge Northumbria University and MMC ENGINEER LTD for the financial support, necessary research facilities, and technical support.

References

[1] S. Navaratnam, T. Ngo, T. Gunawardena, D. Henderson, Performance Review of Prefabricated Building Systems and Future Research in Australia, Buildings. 9 (2019) 38. doi:10.3390/buildings9020038.

[2] E. Generalova, V. Generalov, A. Kuznetsova, Modular Buildings in Modern Construction, Procedia Engineering. 153 (2016) 167-172. doi:10.1016/j.proeng.2016.08.098.

[3] D. O'Neill, S. Organ, A literature review of the evolution of British prefabricated low-rise housing, Structural Survey. 34 (2016) 191-214. doi:10.1108/ss-08-2015-0037.

[4] S. Velamati, Feasibility, benefits and challenges of modular construction in high rise development in United States: A developer's perspective, MSc, Massachusetts Institute of Technology, 2012.

[5] W. Wilson, C. Barton, Tackling the under-supply of housing in England, House of Commons, 2018. http://researchbriefings.files.parliament.uk/documents/CBP-7671/CBP-7671.pdf (accessed 7 May 2019).

[6] Off-site manufacture construction: Building for change, 2nd ed., Authority of the House of Lords, 2018. https://publications.parliament.uk/pa/ld201719/ldselect/ldsctech/169/169.pdf (accessed 7 May 2019).

[7] Modular construction for multifamily affordable housing, 2018. https://cdn.ymaws.com/www.nibs.org/resource/resmgr/oscc/epa-modular-construction-for.pdf (accessed 7 May 2019).

[8] Liew, Y. Chua, Z. Dai, Steel concrete composite systems for modular construction of high-rise buildings, Structures. (2019). doi:10.1016/j.istruc.2019.02.010.

[9] W. Ferdous, Y. Bai, T. Ngo, A. Manalo, P. Mendis, New advancements, challenges and opportunities of multi-storey modular buildings – A state-of-the-art review, Engineering Structures. 183 (2019) 883-893. doi:10.1016/j.engstruct.2019.01.061.

[10] A. Lacey, W. Chen, H. Hao, K. Bi, Structural response of modular buildings – An overview, Journal of Building Engineering. 16 (2018) 45-56. doi:10.1016/j.jobe.2017.12.008.

[11] H. Adeli, A. Karim, Neural Network Model for Optimization of Cold-Formed Steel Beams, Journal of Structural Engineering. 123 (1997) 1535-1543. doi:10.1061/(asce)0733-9445(1997)123:11(1535).

[12] J. Lee, S. Kim, H. Park, B. Woo, Optimum design of cold-formed steel channel beams using micro Genetic Algorithm, Engineering Structures. 27 (2005) 17-24. doi:10.1016/j.engstruct.2004.08.008.

[13] K. Magnucki, M. Maćkiewicz, J. Lewiński, Optimal design of a mono-symmetrical open cross section of a cold-formed beam with cosinusoidally corrugated flanges, Thin-Walled Structures. 44 (2006) 554-562. doi:10.1016/j.tws.2006.04.016.

[14] T. Tran, L. Li, Global optimization of cold-formed steel channel sections, Thin-Walled Structures. 44 (2006) 399-406. doi:10.1016/j.tws.2006.04.007.

[15] J. Ye, I. Hajirasouliha, J. Becque, A. Eslami, Optimum design of cold-formed steel beams using Particle Swarm Optimisation method, Journal Of Constructional Steel Research. 122 (2016) 80-93. doi:10.1016/j.jcsr.2016.02.014.

[16] J. Ye, I. Hajirasouliha, J. Becque, K. Pilakoutas, Development of more efficient cold-formed steel channel sections in bending, Thin-Walled Structures. 101 (2016) 1-13. doi:10.1016/j.tws.2015.12.021.

[17] P. Gatheeshgar, K. Poologanathan, S. Gunalan, B. Nagaratnam, K. Tsavdaridis, J. Ye, Structural behaviour of optimized cold- formed steel beams, Steel Construction. (2020). doi:10.1002/stco.201900024.

[18] N. Degtyareva, P. Gatheeshgar, K. Poologanathan, S. Gunalan, M. Lawson, P. Sunday, Combined bending and shear behaviour of slotted perforated steel channels: Numerical studies, Journal Of Constructional Steel Research. 161 (2019) 369-384. doi:10.1016/j.jcsr.2019.07.008.

[19] G. Perampalam, R. Dobson, K. Poologanathan, K. Tsavdaridis, B. Nagaratnam, E. Iacovidou, Modular Building Design: Post- Brexit Housing, in: The 14Th Nordic Steel Construction Conference, NORDIC STEEL 2019, Copenhagen, Denmark, 2019.

[20] W. Macht, Steel Modules Speed Construction, Urban Land Institute, 2019. https://www.panoramic.com/wp-content/uploads/2018/12/Steel-Modules-Speed-Construction-Macht-W-2019-86-91.pdf (accessed 9 May 2019).

[21] R. Lawson, R. Ogden, R. Bergin, Application of Modular Construction in High-Rise Buildings, Journal of Architectural Engineering. 18 (2012) 148-154. doi:10.1061/(asce)ae.1943-5568.0000057.

[22] Modular Building Institute, Modular.Org. (2013). http://www.modular.org/HtmlPage.aspx?name=why_modular (accessed 7 May 2019).

[23] R. Smith, Off-Site Modular Construction Explained, Off-Site Construction Council, national Institute of Building Sciences, 2016. https://cdn.ymaws.com/www.nibs.org/resource/resmgr/OSCC/OSMC_Explained.pdf (accessed 9 May 2019).

[24] M. Kamali, K. Hewage, Life cycle performance of modular buildings: A critical review, Renewable and Sustainable Energy Reviews. 62 (2016) 1171-1183. doi:10.1016/j.rser.2016.05.031.

[25] Lawson RM, Ogden RG. Sustainability and process benefits of modular construction. In: Proceedings of the 18th CIB World Building Congress, TG57-Special Track. Salford, UK; May 10–13, 2010. p. 38–51.

[26] E. Iacovidou, P. Purnell, Mining the physical infrastructure: Opportunities, barriers and interventions in promoting structural components reuse, Science of The Total Environment. 557-558 (2016) 791-807. doi:10.1016/j.scitotenv.2016.03.098.

[27] L. Aye, T. Ngo, R. Crawford, R. Gammampila, P. Mendis, Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules, Energy And Buildings. 47 (2012) 159-168. doi:10.1016/j.enbuild.2011.11.049.

[28] S. Alonso-Zandari, A. Hashemi, Prefabrication in the UK housing construction industry, in: 5th International Conference on Zero Energy Mass Customised Housing-ZEMCH 2016, 2016.

[29] HNF Property | World's tallest modular building under construction in Croydon, HNF Property. (2019). https://www.hnfproperty.com/worlds-tallest-modular-building-under-construction-in-croydon/ (accessed 10 May 2019).

[30] A. Welch, World's Tallest Modular Buildings, Croydon - e-architect, E-Architect. (2019). https://www.e-architect.co.uk/london/worlds-tallest-modular-buildings (accessed 10 May 2019).

[31] The Height of Design, Tide Construction Limited and Visions Modular Systems UK Ltd, 2018. https://www.buildoffsite.com/content/uploads/2018/07/Tide-and-Vision-Presentation-Buildoffsite-The-Height-of-Design-4th-July-2018.pdf (accessed 10 May 2019).

[32] T. Gunawardena, T. Ngo, P. Mendis, J. Alfano, Innovative Flexible Structural System Using Prefabricated Modules, Journal of Architectural Engineering. 22 (2016) 05016003. doi:10.1061/(asce)ae.1943-5568.0000214.

[33] Melbourne Home to Australia's Tallest Prefabricated Building, The Urban Developer. (2016). https://theurbandeveloper.com/articles/melbourne-home-australias-tallest-prefabricated-building (accessed 10 May 2019).

[34] I. Block, BIG's timber housing in Stockholm is designed to look like a hill, Dezeen. (2019). https://www.dezeen.com/2018/11/09/big-76-park-stockholm-modular-timber-apartments-architecture/ (accessed 13 May 2019).

[35] C. Coello, S. Dehuri, S. Ghosh, Swarm Intelligence for Multi-objective Problems in Data Mining, Springer Berlin Heidelberg, Berlin, Heidelberg, 2009.

[36] CEN, Eurocode 3: Design of Steel Structures, Part 1.3: General Rules—Supplementary Rules for Cold-formed Steel Members and Sheeting, in, Brussels:European Comittee for Standardization, 2006.

[37] CEN, Eurocode 3: Design of Steel Structures, part 1-5: Plated Structural Elements, in, Brussels: European Comittee for Standardization, 2006.

[38] Mathworks, Matlab R2017a, in, Mathworks, Inc, 2017

[39] Abaqus CAE, ABAQUS inc., N/A, 2017.

[40] P. Keerthan, M. Mahendran, New design rules for the shear strength of LiteSteel beams, Journal of Constructional Steel Research. 67 (2011) 1050-1063. doi:10.1016/j.jcsr.2010.11.010.

[41] L. Sundararajah, M. Mahendran, P. Keerthan, New design rules for lipped channel beams subject to web crippling under two-flange load cases, Thin-Walled Structures. 119 (2017) 421-437. doi:10.1016/j.tws.2017.06.003.

[42] P. Keerthan, M. Mahendran, Improved shear design rules for lipped channel beams with web openings, Journal of Constructional Steel Research. 97 (2014) 127-142. doi:10.1016/j.jcsr.2014.01.011.

[43] L. Wang, B. Young, Design of cold-formed steel channels with stiffened webs subjected to bending, Thin-Walled Structures. 85 (2014) 81-92. doi:10.1016/j.tws.2014.08.002.

[44] C. Pham, G. Hancock, Experimental Investigation and Direct Strength Design of High355 Strength, Complex C-Sections in Pure Bending, Journal of Structural Engineering. 139 356 (2013) 1842-1852. doi:10.1061/(asce)st.1943-541x.0000736.

[45] C. Pham, Direct Strength Method of Design of Cold-Formed Sections in Shear, and Combined Bending and Shear, Ph.D The University of Sydney, 2010.

[46] M. Naser, N. Degtyareva, Temperature-induced instability in cold-formed steel beams with slotted webs subject to shear, Thin-Walled Structures. 136 (2019) 333-352. doi:10.1016/j.tws.2018.12.030.

[47] M. Lawson, R. Ogden, C. Goodier, Design in modular construction, 2014.

[48] M. Lawson, Building design using modules, The Steel Construction Institute, 2007.