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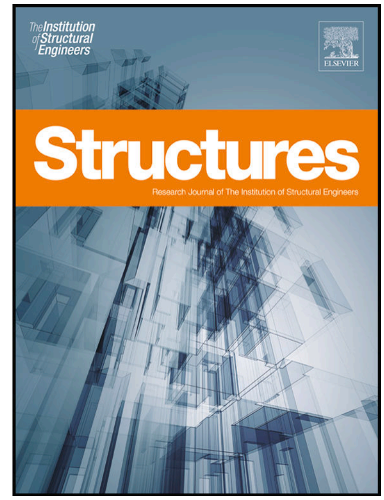

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Development of Affordable Steel-Framed Modular Buildings for Emergency Situations (Covid-19)

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Abstract

This paper presents the development of novel affordable steel-framed modular units for construction with enhanced overall (healthcare, structural, fire, and lightweight) performance, which ideally suits for emergency response situation, such as current covid-19 pandemic. The nature of quick response and well-prepared strategies are essential to cope with the demand of quicker construction for emergency response structures and if similar situation continues or arises in the future as well. Off-site oriented modular construction is ideal to provide these requirements at very short notice for emergencies. Modular units made of steel components are a leading choice due to the exceptional strength and rigidity for lightweight construction. A new weight optimisation procedure was developed for Cold-Formed Steel (CFS) joists in varying shapes of and results show that weight for per unit length of the joists can be reduced up to 24% without compromising structural capacity. This was verified with validated Finite Element (FE) models. In order to improve the faster jointing method, a novel cut and bend intra-module connection was also introduced. In addition, strap bracing is used for the lateral stability of steel-framed modular buildings. Modular breathing panels are proposed to be employed in corner post modules as sidewalls to improve the indoor air quality and reduce the spread of disease. Based on the comprehensive assessment and numerical results conceptual design of performance improved steel-framed corner post modular unit was proposed to offer short-to-medium (in response to emergencies), as well as long-term solutions for the construction industry.

Keywords: Modular building, Emergency situation, Covid-19, Cold-formed steel, Optimum joist design for lightweight, Numerical Studies, Cut and bend connection, Strap bracings, Modular breathing panels, Conceptual design.

1. Introduction

Modular construction is an alternative approach to conventional on-site construction. In contrast to conventional construction methods all major works are performed off-site (within a factory controlled environment) and leaving only the assembly work plus some aesthetic finishing and service connections to be performed on-site [1-3]. That is simply transferring the on-site work to off-site for better efficiency [3]. These volumetric modular units can be formed with steel, timber, concrete, or hybrid materials. However, steel-framed modular units lead over other materials due to structural and sustainable advantages [4]. The advantages of modular buildings play a major role in the growth of this emerging new construction method. Off-site based modular construction methods are fast to construct, high quality, safer construction process, accurate, cost-effective, sustainable, and reduce on-site workers [2, 3, 5-10]. These inherent advantages help the spread of modular techniques over the world to be applied in residential, commercial, educational, and health facility buildings [1, 3, 4, 6, 7, 10].

Since modular construction is different from the conventional construction method, several research studies have been conducted to investigate the structural, fire, energy, seismic performance, challenges, and future opportunities of the modular buildings. To understand the behaviour and performance of the modular buildings, critical review based research [3, 6, 9, 11, 12] has been performed. Research on modular connections (inter module and intra module) has also been investigated as connections are identified as a crucial element for the structural behaviour and the stability of modular buildings. Theoretical, experimental, and numerical investigations are available in the literatures that assess connection stiffness and the force-displacement/moment-rotation behaviours for innovative modular connections, and interlocking systems [8, 11, 13-18]. In parallel to modular research, the light gauge steel area is also subjected to advancements developing innovative structural member profiles to enhance the structural efficiency. Optimisation studies [19-24] have resulted in innovative Cold-Formed Steel (CFS) beam and column profiles with intermediate web and flange stiffeners. The objective of these optimisation studies was to maximise the structural capacity of CFS structural members for a given amount of material. Moreover, modifying CFS beams through providing staggered slotted perforations is efficient to enhance the thermal performance while the effect of staggered slotted perforations on flexural capacity is minimal [25-27]. These findings can be incorporated into steel-framed modular buildings to ensure more economical and efficient design solutions.

All these findings can be combined to develop overall performance improved modular units to address infrastructure need for any emergency. At present, the world is experiencing a pandemic situation due to the spread of covid-19. Health care sectors are dedicating themselves to control this deadly virus. However, the spread of the virus is rapid and it has affected significant numbers of people around the world. This has resulted in the requirement for additional treatment areas such as extensions of hospital buildings and even new hospital buildings, testing centres, separate new accommodations for health care workers, all in a rapid manner. The success of using modular construction to the emergency alike covid-19 can be witnessed in China. In early February in Wuhan, China, a mass 1 000-bed temporary hospital was constructed in 10 days. In the UK, there are well established modular industries to deliver a mass number of modules, for example, ESS Modular Ltd. Fig. 1 depicts a volumetric modular unit produced by ESS Modular Ltd. Therefore, overall performance improved including healthcare innovative modular units need to enter the market understanding the short term (emergency situations) and long-term future demands.

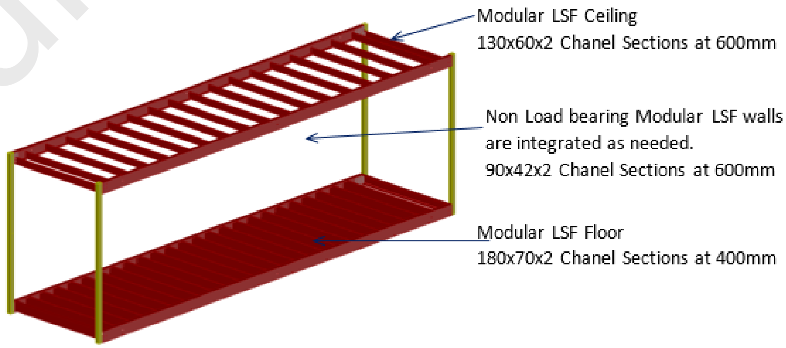


Fig. 1. Volumetric steel-framed modular unit (Courtesy of ESS Modular Ltd)

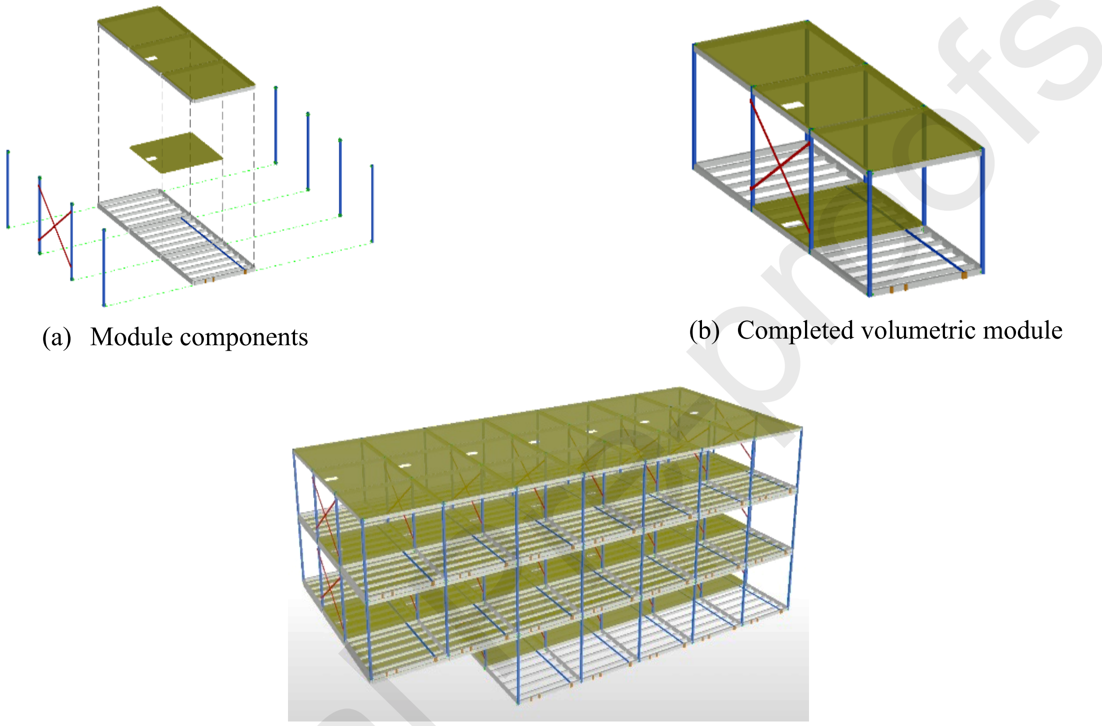
To be a source for well-prepared strategies and understanding the present and future demand, this paper is aimed at developing overall performance improved light gauge steel modular units. The convenience of steel-framed modular construction was deeply investigated to be employed especially in global emergencies like covid-19 and for any upcoming global emergencies. More attention was also provided to develop a structurally stable and performance improved, lightweight healthcare volumetric modular units for emergencies. This was achieved through ensuring modular units composed of the structurally improved essential components such as beams, columns, connections, and bracings and introducing new techniques. The proposal for the overall improved volumetric modular units was supported by optimisation studies, physical testing results, and advanced finite element modelling. Combining all the results, a conceptual design of overall performance improved corner post-modular units is presented to be used for short term and long term needs.

2. Light gauge steel modular construction

2.1. Characteristics and forms of modular construction

Modular construction is a method of construction that differs from other forms of conventional constructional methods. Modules, the basic volumetric element of modular buildings, are prefabricated off-site and deployed to the intended place (on-site) for the assembly and connecting services. Moreover, the process combines various types of manufacturing technologies for rapid construction. The independent engineering in a factory leads to stronger modular buildings compared to conventional buildings [2]. Fig. 2 shows the major stages of the modular construction, factory assembling of a module, completed volumetric module, and completed typical modular building on-site. Modular volumetric units are composed of wall, floor and ceiling panels and bracing (if required). Corner posts are typically provided by hot-rolled steel angles or hollow sections [10]. It is worth noting that the prefabrication of a volumetric module in a factory could be a member basis assembly or a panel base assembly.

In general, modules are categorized into two different forms considering load path. Load bearing wall modules and corner post supported modules are the two generic types and both types of modules are employed in practice [1, 3, 5]. These two types of modules are illustrated in Fig. 3. In load-bearing wall modules, the load is transferred to the foundation through walls while in corner post modules load is transferred to the foundations through corner posts [5] and often intermediate posts too. In a load-bearing steel module, wall studs are generally spaced at 300 mm or 600 mm intervals [3]. Moreover, the modular industry uses different shapes of modules such as slope end module, stepped module, faceted module, and tapered module. However, above all, the rectangular shape module remains common in construction. It should be noted that wall supported modules are compatible with all different shapes while unlikely to be achieved with corner supported modules. Corner post modules are useful for buildings where larger open space is essential. In such a requirement, modules can be placed side by side, on top of another to form a wide variety of building configurations as depicted in Fig. 4. All these characteristics allow modular units to be assembled vertically up to 25 stories gaining the stability from concrete or steel framed core [3].

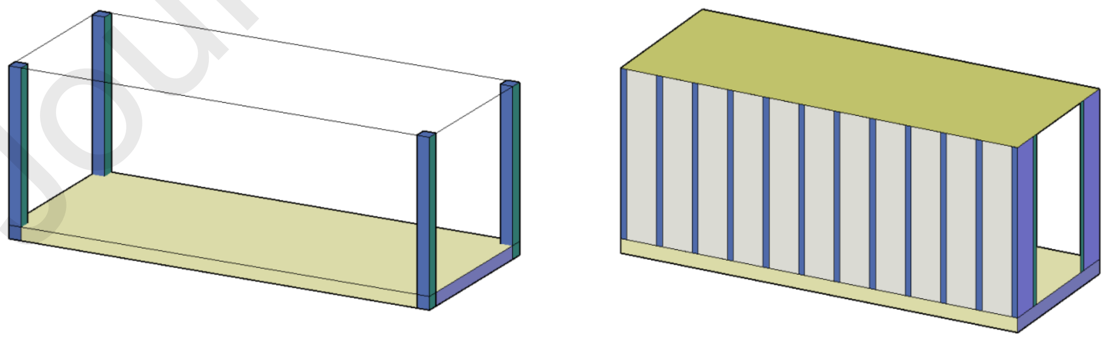


(a) Module components

(b) Completed volumetric module

(c) Completed on-site assembly

Fig. 2 Modular construction: Module assembly to completed modular building



(a) Corner supported modules

(b) Wall supported modules

Fig. 3 Generic types of modules

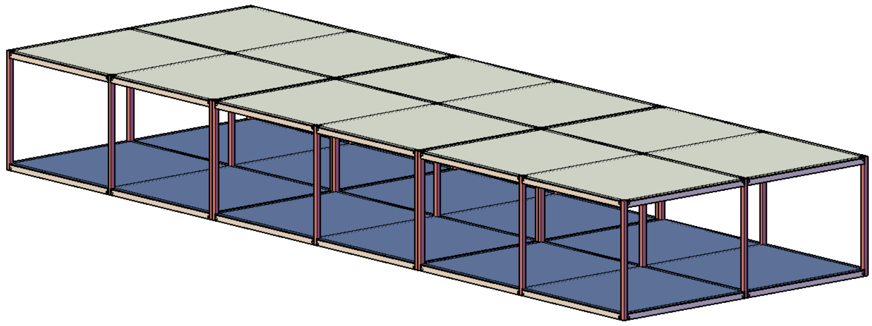


Fig. 4 Corner post modules arranged horizontally to form wider open space

2.2. Steel-framed in modular construction

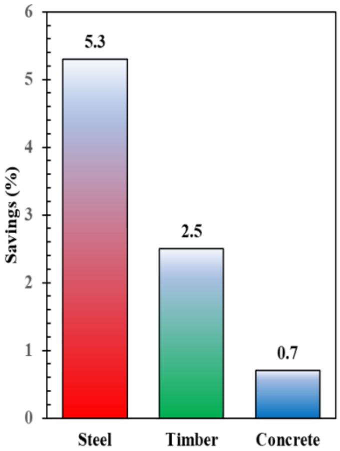
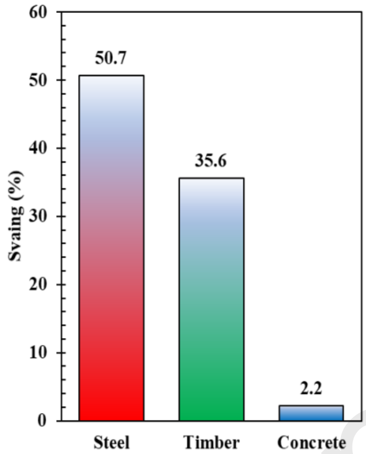
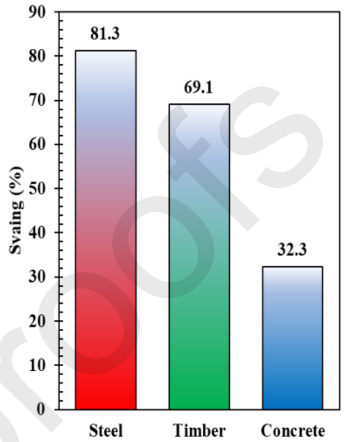
Steel is widely believed as a good option in modular construction as it holds superior characteristics that ideally suit the off-site oriented modular construction. The modular units fabricated with steel members bring significant advantages of superior precision, long term durability, resistance to fire, exceptional strength for low weight, and high sustainability. Existing studies on steel-framed modular buildings further confirm the enhanced performance.

Aye et al. [28] assessed the life cycle energy requirements of modular steel construction, modular timber construction, and conventional concrete construction to determine the environmental impacts. They found that steel is preferred to be employed as modular construction material in terms of its reuse ability. Table 1 presents the potential savings of mass, volume, and embodied energy when steel, timber, and concrete are subjected to reuse. It can be noticed that approximately 50 % of mass, and 80% of embodied energy could be saved when steel is reused while other timber and concrete material shows lower reuse benefits.

Furthermore, a typical steel modular unit weighs approximately 15-20t while the weight of a typical modular unit made of concrete is approximately 20-35t. Thus steel modular units result in 20-35% lightweight compared to the concrete modular unit [5]. Fig. 5 shows the weight proportion of a steel modular unit. CFS members are small and higher yield strength can be achieved. This would produce lightweight modular units [4].

Steel modular buildings are also fast to construct as modules are connected using bolted and rivetted connections whereas concrete modular units are connected through in-situ grouting techniques which increase on-site working time [5]. This offers demountable buildings. Thus modular units can be disassembled and transported to another site for assembly. Therefore, the use of sustainable material such as light gauge steel into modular construction becoming vital considering present and future environment, such that construction material should be reusable.

Table 1: The percentage of potential savings achieved from the reuse of steel compared with other materials[28]

Volume Saving	Mass Saving	Embodied energy saving
		

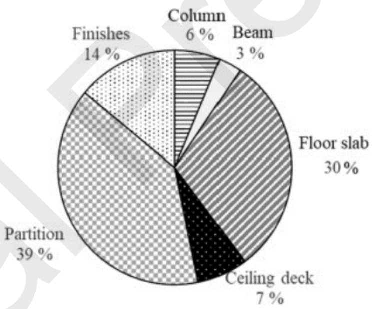


Fig. 5. Weight proportion in a sample steel modular unit [5].

3. Role of modular construction in emergency situations

3.1. General

The outbreak of novel coronavirus, named covid-19, has brought the entire world to a standstill and has certainly had a huge effect on everyone's lives worldwide. As this major global pandemic shuts schools and industries, vital facilities such as hospitals and food services, work overtime to fulfil rising demand. The growing need exceeds the capacity of most communities to respond where health care infrastructures such as individual testing and temporary supply storages are concerned. It is without a doubt imperative to provide a suitable clinical space that meets the requirements needed for treating the virus or to support spaces to replace areas that are re-appropriated for high dependency environments. The modular construction system has gained growing attention during this present covid-19 emergency due to adjustable construction potentials. Investigation into this is beneficial for the present situation and any upcoming pandemics.

3.2. Modular buildings as the formula for rapid response for covid-19

The growth of the pandemic has resulted in the imperative need of the rapid creation of emergency facilities such as testing and treatment centres, critical care or first aid facilities, command centres, administration offices, wash facilities and restrooms, distribution centres for essential services, portable training facilities and storage for medical supplies and equipment [29]. In recent years, modular buildings have been introduced in many sectors including educational, commercial, healthcare, hospitality, and many similar others. Among these, the health sector is highly anticipated to see lucrative growth. It is possible that prefabrication and/or modular construction is viewed as the most viable option by most health care providers and investors [30]. Further, the healthcare sector utilises about 49% of modular construction in the United States which indicates the appropriateness of using modular construction in healthcare emergencies [31]. Therefore, modular building construction can serve as a key contributor to battle against covid-19. Fig. 6 shows modular units which has been prepared to supply covid-19 emergency.

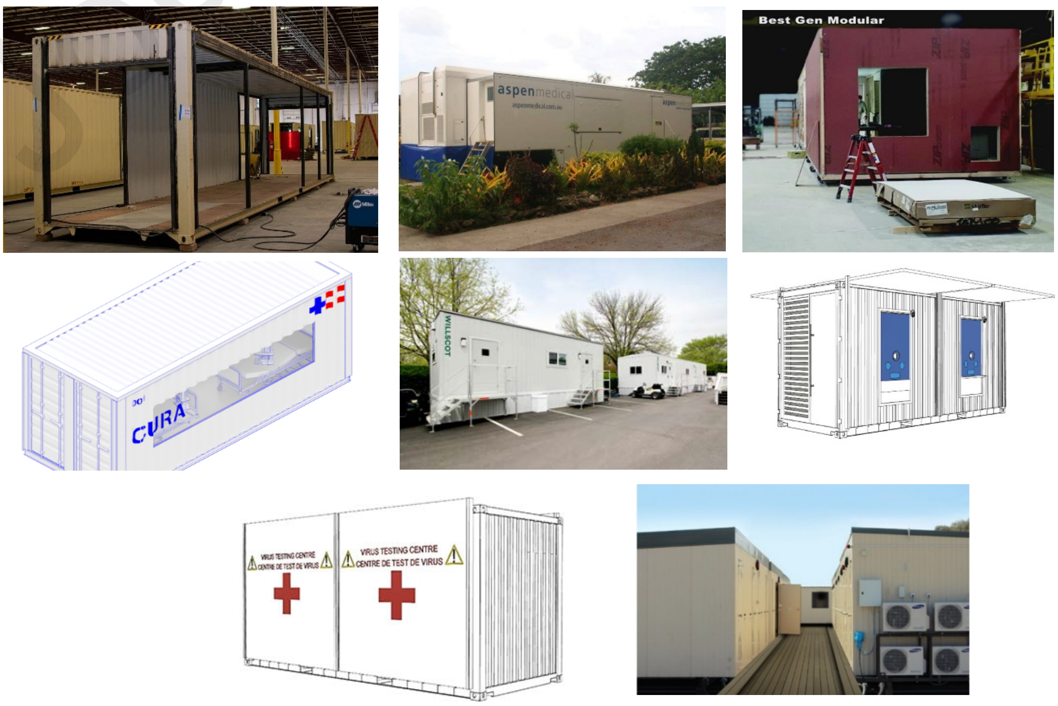


Fig. 6. Modular units constructed for covid-19 emergency [32-38]

The spread of the covid-19 virus is currently unstoppable, and it results in a high number of affected persons. Therefore, existing facilities and space requirements are not adequate to treat all affected people. This leads to the requirement of additional spaces and hospital extensions however in a rapid manner. Fast-built techniques can be achieved through modular construction. Hough and Lawson [1] highlighted the importance of using modular construction in hospital extensions. They state that due to the reduced disruption nature of modular construction, the modular units can be employed in rooftop extensions to hospitals. To add up with Hough and Lawson's [1] points, prefabrication also significantly eliminates disruptions in functioning healthcare facilities with decreased traffic, noise, and dust, which is highly essential when building up or expanding an infrastructure facility around patients with weakened immune systems. Therefore, in-housed patients will experience almost no inconvenience in terms of excess noise and other disruptions. Modular helps to enlarge the hospital places as quarantine centres and creates new places to accommodate new ICU beds [29]. Fig. 7 shows the constructed hospital using prefabricated modules across the world. Thus, factory designed, manufactured, and onsite installed modular buildings are the best-suited approach to address the complexity of challenges now confronting the healthcare system.

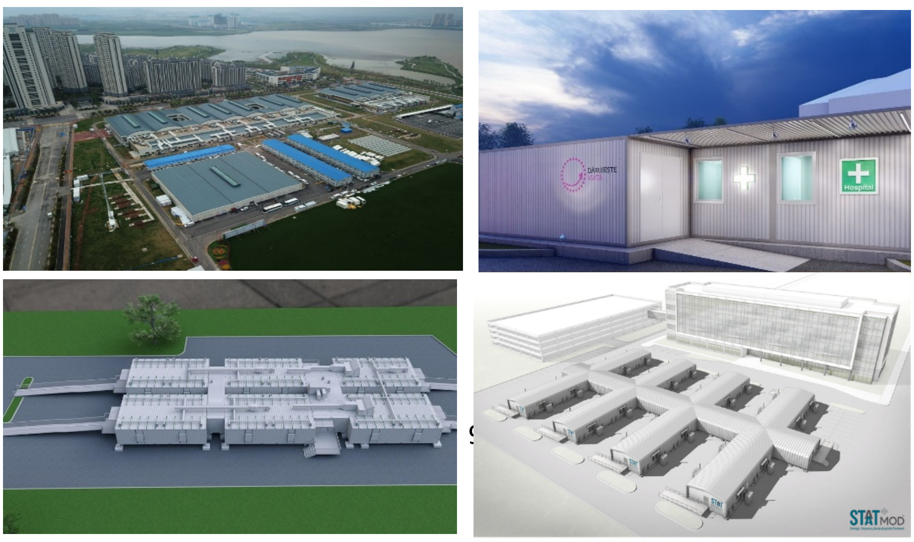


Fig. 7. Hospital constructed using modular techniques across the world [29, 32, 39, 40].

Building companies are considering how best they can participate in the country's quest for private sector action in order to improve the supply of hospital beds and other critical medical facilities, the related underlying infrastructure and the capacity to support National Health Services (NHS) estates [31, 36]. This is toadied by the fact that modular builders across the world are engaged in the design and development of medical infrastructure that can be delivered on time when are where required [38]. The modular builders and contractors are also preparing not only to fulfil the demand for health care infrastructure in terms of quantity but also how to fulfil the spectrum of demands fast [41]. Fig. 8 shows the spectrum of solutions and execution strategy by Horizon North [41].

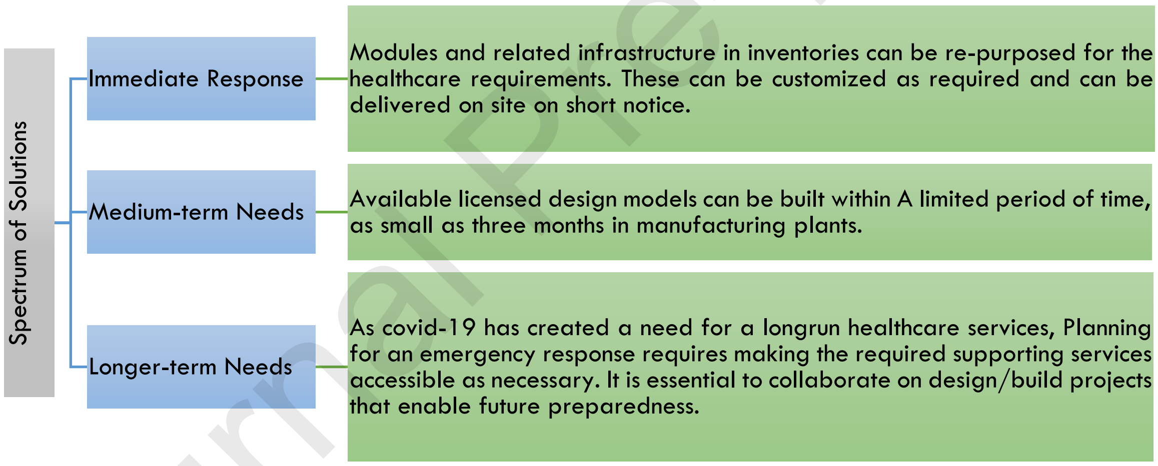


Fig. 8. The spectrum of solutions and execution strategy by Horizon North for covid-19 [41]

It is noteworthy to investigate the safety of construction operatives who are involved in building modular units. One of the most important features of modular buildings is that it distinguishes the area where the building is being constructed and the supply of local labour needed for the traditional construction of the building. Labourers work in a controlled environment. Factories may, therefore, be able to build and deliver healthcare modular units, if necessary [42-44].

The modular units can be shipped to NHS sites in days through well-managed supply chains, in time to respond to the anticipated rise in demand [45]. This is possible because manufacturing off-site allows multiple building elements to be constructed simultaneously and assembled on-site. Already prefabricated modules can be tailored to specific needs from housing to health care units. Modular components and units can be manufactured and can be stored in storage ready to install any time when and where necessary. Furthermore, modular units, which are designed to target the covid-19 pandemic can also be planned and customised to adopt possible future transformation or conversion to be used for different requirements after the epidemic comes to control [3, 36, 46, 47]. Thus there is no wastage of funds.

3.3. Application of modular buildings across the world for covid-19 pandemic

Modular building is a appropriate solution to solve major problems related to the health sector as fast track construction cannot happen by the means of conventional construction methods using brick, timber, and concrete buildings. That is where modular could come to the rescue. Hence modular buildings are indeed expected to be used by several countries in order to provide quarantine facilities, isolation wards, testing labs, resting facilities to medical staff, and so on. Therefore, a modular solution has a unique advantage to the healthcare system in a crisis.

Table 2 demonstrates the examples of where the modular concept is used to provide healthcare facilities in a compact timeline during the covid-19 pandemic period. A good example of the use of modular construction to build hospitals within a short duration can be seen in China. Following the 2020 epidemic of covid-19, the Chinese authorities were confronted with a significant rise in the number of patients in desperate need of hospitalization and treatment. To address this issue, modular building construction technique was used in early February in Wuhan, China, the epicentre of coronavirus outbreak, to create a 1,000-bed temporary hospital. The facility was estimated to have taken just 10 days to build which is a revolutionary step of success in the history of modular building construction [48-50]. Fig. 9 compares the before and after images of the Huoshenshan Hospital being built in Wuhan. Just within three days after, china opened its second 1600 bed hospital in the city, Leishenshan. These two hospitals being the major part of China's battle against the coronavirus – were made possible in record time only because of the use of modular techniques [48]., these hospitals were constructed placing the steel modular units on concrete foundations [29].

These real-world examples have shown the potential of modular building to address the rapid need of medical infrastructure. It is worth noting that the present world should be prepared for any upcoming pandemics. Therefore, the development of modular units with enhanced overall performance in terms of structural and non-structural aspects remains necessary.

Table 2: Recently used modular construction for the emergency situation

Country	Design	Short description	Construction/ delivery time	Reference
Italy	CURA pod	The name stands for "Connected Units for Respiratory Ailment". It is plug-in intensive caring units and fast to be to mounted as hospital tent.	_	[35]
UK	ICU wards	Two new intensive hospital care units to cover extra capacity requirement	3 weeks	[51]
USA	Social distancing units	66 units, each 40′ x 8′ high quality units that are being used for social distancing with an additional 20′ storage unit used to hold extra materials.	4 months	[36]
USA	Portable virus testing centre	Built from prefabricated connex modules and can be used for walk-up or drive-thru applications to test for covid-19 infections.	2-3 weeks	[37]
USA	STAAT Mod	Temporary hospital system to handle the surge capacity during a virus crisis. Capable of providing airborne infection isolation rooms with advanced air handling and filtration system.	3-4 weeks	[40, 49]
Australia	Emergency triage and consultation room	A predesigned classic modular medical treatment rooms featuring high-quality furniture and equipment.	-	[38]
Armenia	Extension of Yerevan's Nork hospital	Extension of Nork infectious diseases hospital by adding 42 more wards by installing modular section	10 days	[52]
China	Huoshenshan hospital	A new 1000 bed temporary hospital to treat covid-19 patients using modular building construction	2 weeks	[29, 48]
China	Leishenshan hospital	A new 1600 bed temporary hospital to treat covid-19 patients using modular building construction	2 weeks	[29, 48]
Georgia	Temporary Georgia hospital	Construction of a new modular hospital comprising 24 patient rooms and auxillary rooms including all facilities.	4 weeks	[32]
USA	IQR	New isolation and quarantine site (IQRs) comprise 8 modular units to accommodate 31 people.	-	[53]
UK	New wards	Construction of a 20-bed isolation ward for the hospital to increase the capacity	8 weeks	[54]
Australia	Field hospital	Series of demountable modular medical care buildings to treat covid-19 patients	-	[33]
Romania	Hospital	Construction of a 50-bed modular hospital in the courtyard of the existing hospital to treat covid-19 patients	4 weeks	[39]

Canada	Hospital	A new 93-bed modular structure in the hospital ground to accommodate the surge of patients	-	[55]
USA	Quarantine facility	A 40-bed facility is built using modular cube pods containing micron filtration and negative air pressure system	2 weeks	[56]
USA	Hospital rooms	New 5000 hospital rooms with all negative pressure H-VAC system, and easy cleaning and sanitization facilities.	45 days	[34]

Fig. 9. Before (left) and after image (right) of the Huoshenshan Hospital in Wuhan, China [50]

4. Development of affordable modular unit

4.1. General

This section describes the detail on the development of an affordable modular unit that can be used for a wide range of applications including health care needs. Lawson et al.[3] described how modular building design is governed by the structural, fire, and service requirements. In addition, maintaining a healthy environment should also be considered in modular building design based on the lesson learned from covid-19. Construction efficiency and productivity of the modular construction need to be maximised [5]. This would contribute to providing an adequate building at short notice during any emergency situations.

The importance of considering the structural response of modular buildings may vary based on the location. Moreover, there are no studies to identify how to select the optimal design of modular units [11]. Therefore, this section aims to develop an affordable modular unit considering structural, fire, lightweight, and health-related aspects.

4.2. Material efficient design of cold-formed steel joists

In a steel-framed corner post modular unit the gravity load is carried by floor joists and then transferred to corner posts. Research on modular buildings has been reported that there is a need for lightweight modular units to overcome transportation difficulties and limitations of the lifting tower crane capacity [5]. Lecay et al. [11] suggested the necessity of greater flexibility in the internal layout of modular buildings and proposed that structural member sizes need to be reduced. Hence, an optimisation technique was employed in the present study to optimise CFS floor joists for modular building applications in order to ensure lighter modular units without harming the structural performance.

4.2.1. Optimisation of cold-formed steel floor joists

Optimisation is a unique approach to be employed in structural engineering design for more efficient design requirements. Here, the focus was to develop CFS floor joists with reduced material consumption. The optimisation was performed considering the section moment capacity of the CFS joists. The possibility of using different types of cross-sectional shapes with reduced material usage for a given amount of section moment capacity was investigated. Initially, a commercially available Lipped Channel Section (LCS) was set as a reference to evaluate the degree of material saving when different types of cross-sections are introduced. The considered LCS is commercially available in the light gauge steel construction market therefore comparing the results related to this reference LCS will give a good insight on novel cross-sections. Fig.10 shows the considered reference LCS joist. This section has the following mechanical and dimensional properties:

- Yield strength (f_y) = 450 MPa
- Modulus of elasticity (E) = 210 GPa
- Poisson's ratio (v) = 0.3
- Total coil length (L) = 415 mm
- Thickness (t) = 1.6 mm
- Internal bent radius (r_i) = 2t

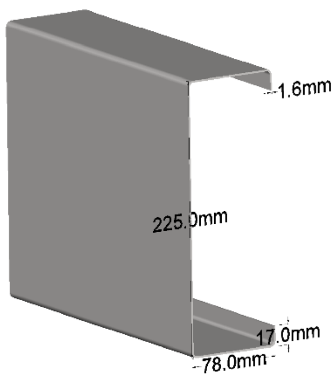
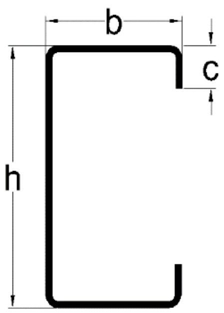


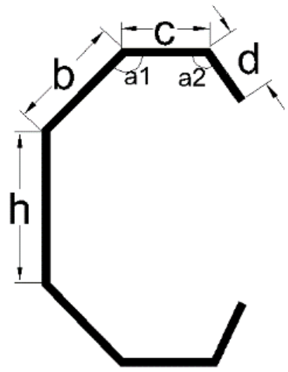
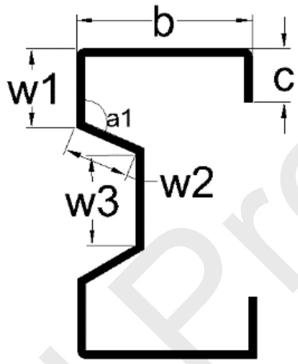
Fig. 10. Reference LCS beam (outer-to-outer dimensions)

The section moment capacity of this reference section is 11.35 kNm based on Eurocode 3 [57, 58] calculations. The optimisation is intended to minimise the coil length without compromising the section moment capacity. To achieve this, different shapes (LCS, Folded-flange, and Sigma) of CFS floor joist cross-sections were considered. Minimum coil length required for LCS, Folded-flange, and Sigma sections to achieve the section moment capacity of 11.35 kNm was determined. Table 3 presents the selected prototypes and the employed optimisation constraints based on Eurocode 3 [57, 58]. In addition to that suitable practical and possible manufacturing constraints also were included in the optimisation problem. This ensures the practicality of the output section dimensions and shapes. The total height of the sections was limited to 300 mm while the minimum width of the flange (b) was maintained to 50 mm to ensure an adequate connection with floorboards. Furthermore, the minimum depth of the lip (c) was taken as 15 mm.

The optimisation was performed using Whale Optimisation Algorithm (WOA). This algorithm was introduced in 2016 admiring the social and hunting behaviour of humpback whales. The bubble-net hunting strategy of humpback whales has been simulated in the algorithm to obtain the optimum solution [59]. The relevance of employing this optimisation algorithm was verified with 6 classical structural design problems including 15, 25, and 52 member truss design problems [59]. Therefore, WOA was used to optimise the CFS floor joists. Initially, the procedure to determine the section moment capacity was developed based on Eurocode 3 [57, 58] provisions. The effective width calculation procedure described in Ye et al.[22] and Qiang [60] was followed to determine the section moment capacity of folded-flange and sigma sections, respectively. Both bending failures subjected to local and distortional buckling were considered and the lowest was taken as the section moment capacity.

Table 3: Considered cold-formed steel floor joist shapes and optimisation constraints based on Eurocode 3

Cold-formed steel section	Optimisation variables	Optimisation constrains [22, 57, 58]
Lipped channel section (LCS)		$b/t \leq 60$ $c/t \leq 50$

		$h/t \le 500$ $0.2 \le c/b \le 0.6$
Folded-Flange	 	$30 \le b \le 48$ $50 \le c \le 60$ $16 \le d \le 60$ $h/t \le 500$ $105° \le a1 \le 150°$ $45° \le a2 \le 135°$
Sigma	 	$b/t \le 60$ $c/t \le 50$ $0.2 \le c/b \le 0.6$ $15 \le w1 \le 60\ (practical)$ $15 \le w2 \le 30\ (practical)$ $30 \le w3 \le 200\ (practical)$ $90° \le a1 \le 175°\ (practical)$

The section moment capacity objective functions and WOA optimisation procedure for LCS, folded-flange, and sigma sections were developed in MATLAB programme. The objective function for optimisation can be written as follow:

Consider $x = [x_1, x_2, x_3, \ldots\ldots, x_N],\ N = No.\ of\ design\ variables$

$$\text{Minimize}\quad \left.\begin{array}{ll} L(x) = h + 2(b + c) & for\ LCS \\ L(x) = h + 2(b + c + d) & for\ Folded-Flange \\ L(x) = w3 + 2(b + c + w1 + w2) & for\ Sigma \end{array}\right\} \quad (1)$$

Subjected to $M(x) = M_{Reference}$

Variable range $x_i^{Lower} \leq x_i \leq x_i^{Upper}$, $i = 1, 2,\ldots,N$

Here, $M_{reference}$ is the section moment capacity of the reference section which is 11.35 kNm. x_i^{Lower} and x_i^{Upper} denote the implemented lower and upper bound of the design variables which were set based theoretical and possible manufacturing constraints.

4.2.2. Optimisation results of cold-formed steel floor joists

The optimisation problem was aimed to minimise the total coil length (weight) of the CFS floor joists without compromising the section moment capacity of 11.35 kNm. Mirjalili and Lewis [59] used 30 search agents and 500 iterations to obtain the optimum solution using WOA for a 52 member truss problem. They proposed that 100 search agents and 1000 iterations would be adequate to obtain an optimal solution. However, a higher number of search agents and a maximum number of iterations were used in the present study in order to escape from any local minima. The optimised dimensions were presented in Table 4 while Table 5 shows the amount of weight saved when optimum CFS joists are employed in modular buildings.

Table 4: Dimensions and section moment capacity of optimum cold-formed steel joists

Sections	h (mm)	b (mm)	C (mm)	D (mm)	w1 (mm)	w2 (mm)	w3 (mm)	a1 (°)	a2 (°)	M (kNm)
LCS_Reference	225	78	17	-	-	-	-	-	-	11.35
LCS_Optimised	209.5	50	22	-	-	-	-	-	-	11.35
Folded-Flange	107	48	50	15	-	-	-	105	87	11.35
Sigma	-	50	15	-	60	17	30	149	-	11.35

Table 5: Material saving (weight) of optimum cold-formed steel joists

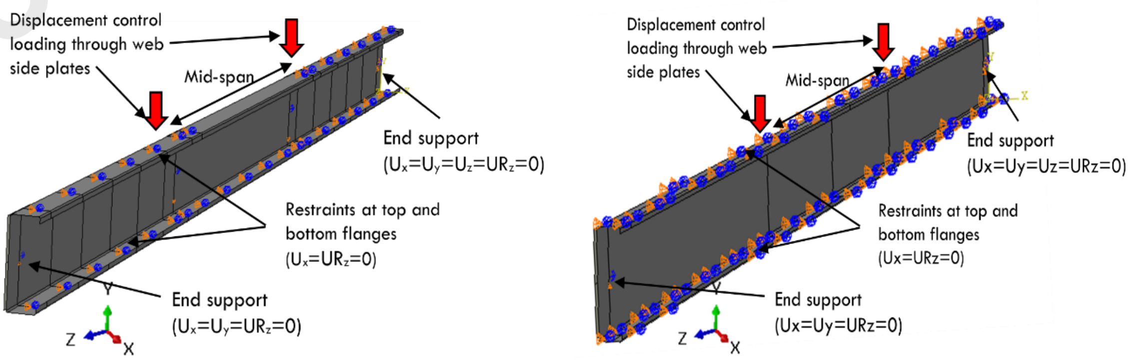
Sections	M (kNm)	Reference and optimised coil length		Per meter weight of the joist		Wight saving ratio [W_{Opt}/ W_{Ref}]
		L_{Ref} (mm)	L_{Opt} (mm)	W_{Ref} (kg/m)	W_{Opt} (kg/m)	
LCS_Reference	11.35	415	-	5.21	-	1.00
LCS_Optimised	11.35	-	353.5	-	4.44	0.85 (15%)
Folded-Flange	11.35	-	333	-	4.18	0.80 (20%)
Sigma	11.35	-	314	-	3.94	0.76 (24%)

The results from Table 4 and Table 5 demonstrate that potential outcome could be achieved through this material based optimisation procedure. When LCS was subjected to optimisation it resulted in 15% per meter weight reduction compared to reference LCS, however, without compromising section moment capacity of 11.35 kNm. Furthermore, the introduction of new shapes such as folded-flange and sigma sections resulted in a notable weight reduction of 20% and 24%, respectively. It is worth noting that these weight reductions are only for per meter length of the beam. For example, instead of using a 1 m length of reference LSC floor joist when Sigma section is employed 1.27 kg of cold-formed steel can be saved without any reduction of section moment capacity. Therefore, for mass production of CFS joists, this will cut down the excess use of material substantially.

Moreover, the application of these optimum CFS joists in the modular building will result in a lightweight modular unit. This helps to address the current challenges related to modular buildings such as weight limitation during the transportation phase and limited lifting tower crane capacity during the assembling phase. Liew et al. [5] reported that the tower crane cost will enhance up to 60% when the lifting requirement cross over 20t. Hence, CFS floor joists which are optimised considering material saving (weight) into account not only contribute to weight reduction but also leads to cut down additional cost.

4.2.3. Finite element modelling of the optimised cold-formed steel joists

FE modelling was aimed to verify the accuracy of the optimisation process by determining the section moment capacity of the optimised floor joists presented in Table 4. In addition, FE modelling is an effective tool to evaluate the pre-and post-buckling behaviour of the optimised CFS floor joists. Non-linear FE models were developed taking geometrical and material imperfections into account in ABAQUS [61]. The bending behvaiour was investigated through modelling the joists as a four-point bending set-up with simply supported boundary conditions. The intended local buckling failure at the mid-span can be achieved through restraining the flange rotation at regular intervals while distortional buckling failure can be achieved allowing flanges free to rotate (see Fig. 11).



(a) Distortional buckling (b) Local buckling

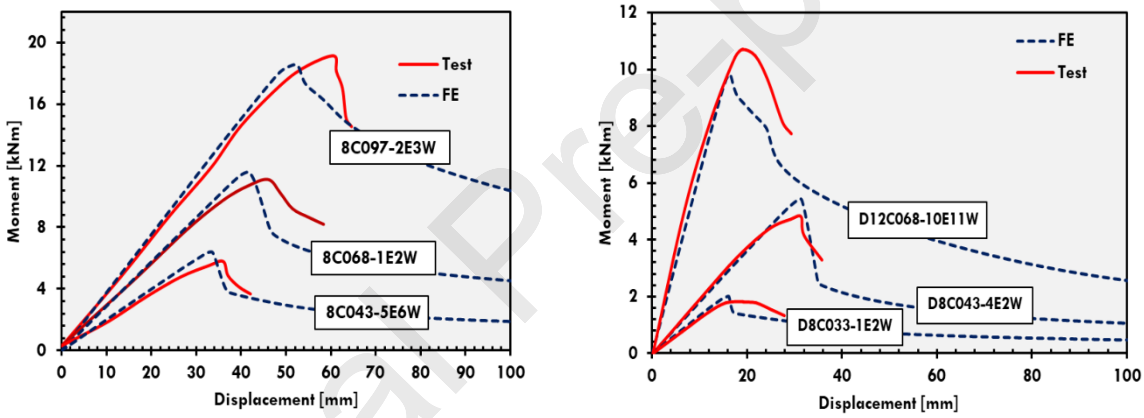
Fig. 11. Finite element modelling arrangement for bending failure subjected to distortional and local buckling

Appropriate element type, mesh refinement, geometric imperfections, material models, analysis methods were selected based on the previous research studies on CFS member modelling [19, 22, 62-65]. Due to the thin-walled nature of CFS members, joists were modelled as S4R shell elements. 5 mm × 5 mm mesh size was employed to refine the CFS joists while the web side plates, which were attached to the web at loading and end support points were refined with 10 mm × 10 mm. These web side plates were attached to the CFS beam using the 'tie' constraint available in the ABAQUS. It is worth noting that corner regions were refined with finer mesh sizes (1 mm × 5 mm) as these regions are critical. The effect of geometric imperfection was included in the non-linear FE model by performing linear buckling analysis. The critical buckling mode and relevant imperfection magnitude were incorporated into FE model using *IMPERFECTION command. Here, the imperfection magnitude of 0.34t and 0.94t were considered for local and distortional buckling, respectively as proposed by Schafer and Pekoz [66]. The stress-strain relationship of the CFS was considered to be elastic-perfectly plastic behaviour with a nominal yielding point. Moreover, the residual stresses and corner strength enhancement were not included in the FE model. This is because both effects approximately offset each other [62]. This type of simplified relationship has been successfully used by past research studies of CFS members subjected to different loading conditions [63-65, 67]. The solution schemes of both 'static-general' and 'static-riks' methods were investigated. It was noticed that there is no difference (less than 1%) in the ultimate capacity obtained from two solution schemes. Therefore, results obtained from the static general method are reported herein.

The aforementioned modelling characteristics were validated against the 3 local buckling and 3 distortional buckling test results reported by Yu and Schafer [68, 69]. Table 6 presents the comparison of the section moment capacities obtained from experiments and FE modelling. The section moment capacities predicted from FE models showed a good agreement with experiment results with a mean and a Coefficient of Variation (COV) value of 0.96 and 0.09 respectively. Furthermore, the comparison of load-displacement response and failure mode comparison is depicted in Fig 12 and 13. Validation results show that the developed FE models are capable of predicting the section moment capacities of CFS joist subjected to both local and distortional buckling, pre-and post-buckling behaviours. Therefore, validated models are appropriate to investigate the bending behaviour of optimum CFS joists such as LCS_optimised, folded-flange, and sigma.

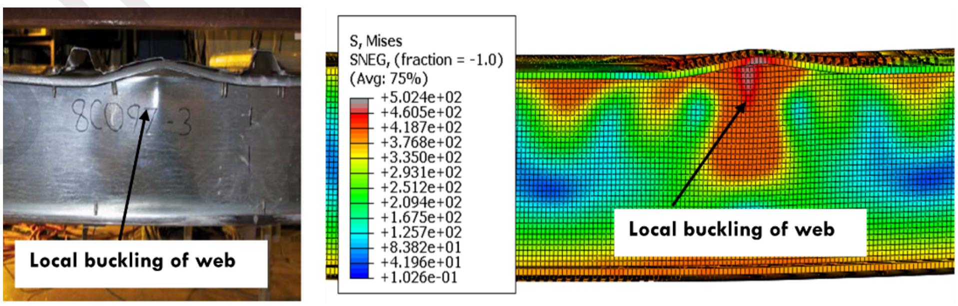
Table 6: Comparison of the section moment capacities between test and FE modelling.

Test type	Sections	Ultimate capacity (kNm)		Test/FE
		Test	FE	
Local buckling [68]	8C097-2E3W	19.50	18.54	1.05
	8C068-1E2W	11.10	11.60	0.96
	8C043-5E6W	5.80	6.41	0.90
Distortional buckling [69]	D8C043-4E2W	4.80	5.43	0.88
	D8C033-1E2W	1.80	2.01	0.90
	D12C068-10E11W	10.70	9.82	1.09
Mean				0.96
COV				0.09

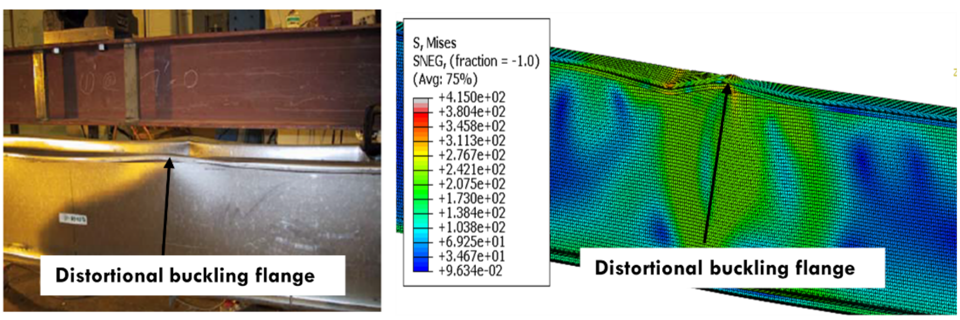


(b) Local buckling (a) Distortional buckling

Fig. 12. Comparison of load-displacement response between [68-70] test and FE modelling



(b) Local buckling failure of 8C097-2E3W section



(a) Distortional buckling failure of D12C068-10E11W section

Fig. 13. Comparison of load-displacement response between test [70] and FE modelling

From Eurocode 3 [57, 58] calculations it was found that for LCS_Benchmark, LCS_Optimised, folded-flange, and sigma sections, section moment capacity subjected to distortional buckling is critical. Therefore, these sections were assessed for distortional buckling in FE modelling. Similar mid and adjacent span lengths as in Yu and Schafer's [69] tests were considered for the four-point bending modelling. Fig. 14 shows the failure modes obtained from FE modelling for the optimum CFS joists. A clear bending failure was observed with flange and web buckling at the compression zone. The section moment capacities obtained from FE modelling for the optimum CFS joists are presented in Table 7. These FE modelling capacities of the optimum CFS joists were compared with the Eurocode 3 [57, 58] and direct strength method based capacity predictions. The comparisons demonstrate that the average maximum deviation of 5 %, thus ensures the accuracy of the optimisation procedure. Moreover, the load-displacement response of the optimum CFS joist is illustrated in Fig.15. Therefore, these optimum CFS joist such as LCS_Optimised, folded-flange, and sigma sections would be a potential option to economise the steel-framed modular buildings and reduce the weight of the structure.

Table 7: Material saving (weight) of optimum cold-formed steel joists

Sections	Section moment capacities (kNm)			Comparison		
	EC3	FE	DSM	FE/EC3	DSM/EC3	FE/DSM
LCS_Reference	11.35	12.92	12.50	1.14	1.10	1.03
LCS_Optimised	11.35	12.08	11.62	1.06	1.02	1.04
Folded-Flange	11.35	11.80	12.83	1.04	1.13	0.92
Sigma	11.35	10.63	10.55*	0.94	0.93	1.01
Mean				1.04	1.05	1.00
COV				0.08	0.09	0.06

Note: *DSM capacity based on Wang and Young's [71] DSM proposal

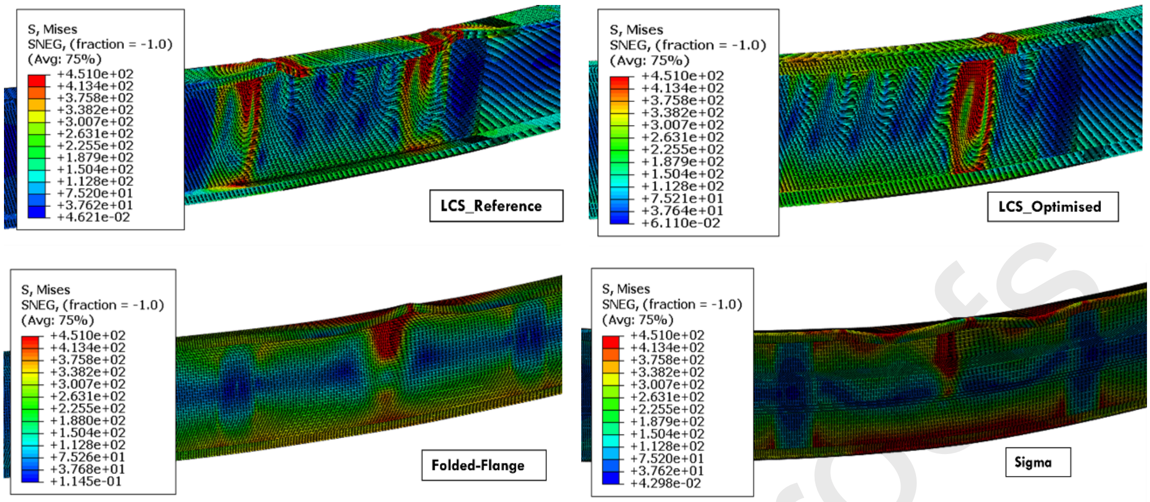


Fig. 14. Bending failure modes of optimum CFS joists

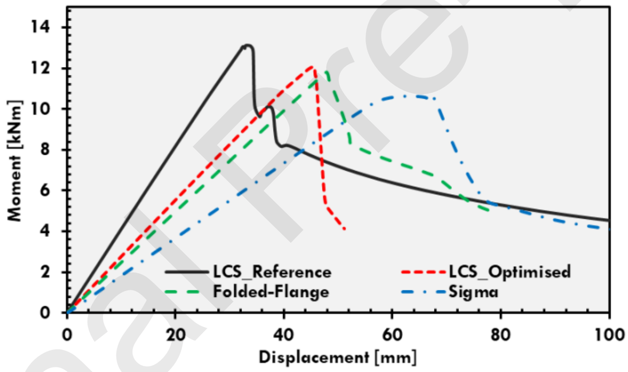


Fig. 15. Moment-displacement behaviour of optimum CFS joists

4.3. Bracing

In steel-framed modular buildings, modules should have the capability to withstand the lateral loads to ensure the stability of the building subject to wind loads and accidental actions. Corner post modules have wider open space in contrast to four-sided modules and have the requirement of a bracing or racking system to ensure the stability against lateral loads. The recent experimental testing demonstrated that 150 mm strap bracing has the potential of carrying a significant load (15 kN) compared to k-bracing (1 kN) and other conventional bracing systems [72]. Figure 16 illustrates the tested specimen with 150 mm strap bracings.

Fig. 16. Tested frame with 150 mm strap bracing [72]

Moreover, Liew et al. [5] suggested that in steel-framed modular buildings bracing method can be further improved with the incorporation of a damper system in order to absorb the energy under seismic conditions. Fig. 17 shows the proposed bracing system by Liew et al. [5] with dampers. Another study suggests that for corner supported modules, the lateral stability can be provided through cross bracings [4].

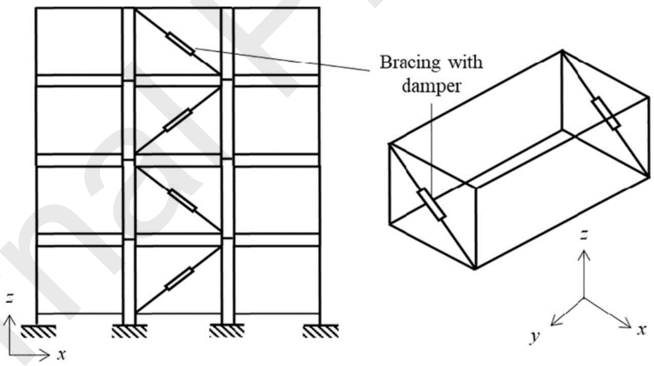


Fig. 17. Steel bracing with dampers for modular buildings [5]

These findings such as strap bracing and proposals related to the bracing system are proposed to be incorporated into modular buildings to enhance lateral stability. However, in terms of lateral stability further studies are required for steel-framed modular high rise buildings [4].

4.4. Fire performance

Research on the fire performance of modular buildings is a developing area [11]. Lawson et al.[3] states that load applied to light steel walls and modular floor, placement of fire barriers between the modules, and limiting the heat transfer through panels are the four aspects in concern with fire resistance of the modular building. Modular building construction has the double skin nature of panels. Unlike a conventional building, there are two beams between the lower and upper module. In general practice, a gap is allowed in between floor and ceiling panels (see Fig. 18) in order to provide external access to inter-module connections [5, 11]. This acts as a barrier for the fire spread from the lower module to the upper module and also increases the acoustic performance [3].

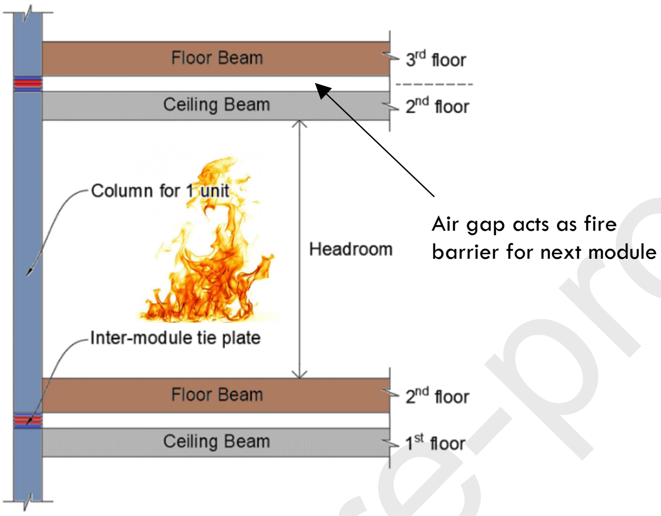


Fig. 18. Air gap between the modules

To further enhance the fire performance of a novel trend of staggered slotted perforated CFS channels can be employed. This staggering nature of slotted perforations contributes to the enhanced fire performance interrupting the direct heat flow path in the web. Fig. 19 shows the staggered slotted perforated cold-formed steel channel. The structural performance of these channels, when it is used as a beam, was investigated by Degtyreva et al. [25-27] and found that the reduction of the maximum reduction bending capacity is only 23% and 11% for distortional and local buckling failure. Moreover, Gatheeshgar et al.[73] introduced these staggered slotted perforations to optimised CFS beams for modular building applications. Therefore, the concept of staggered slotted perforations is proposed to be incorporated into steel-framed modular buildings to limit the heat transfer through panels.

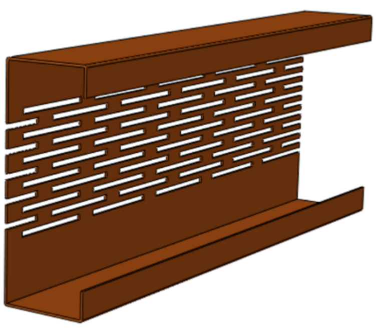


Fig. 19. Staggered slotted perforated CFS channels

4.5. Connections

In modular buildings, connections can be categorised into three main categories: Inter module connections; Intra-module connections; and module-to-foundation connections [11]. Inter module connections connect adjacent modules while all the connections within the module fall into the category of intra-module connections. Developing a reliable connection system is a major challenge [11] and semi-rigid connections are preferred to connect modules rather fully-rigid connections (welded) to maintain the construction speed and efficiency [5]. When it comes to an emergency situation, for example like covid-19, off-site fabrication should speed up to meet health care needs.

The cleat plate connection method is widely used for intra-module connections where the cleat plate is introduced to connect joist and bearer as shown in Fig. 20. However, aiming for faster jointing a new cut and bend connection is proposed in this study which eliminates the need for a cleat plate. Thus saves additional use of material. Here a rectangular cut is made at only three edges and then is bent orthogonally to connect with joists. Fig. 21 shows the newly proposed cut and bend connection method for LCS sections. The number of cuts can be more than one depending on the requirement.

The proposed cut and bend connection is convenient for different shapes of joists such as folded-flange and sigma sections. For the sigma section, 3 cuts can be made to connect two outer and inner web. Fig. 22 shows the proposed cut and bend intra-module connection method for sigma sections. Moreover, it is worth mentioning that the holes resulting from the cuts can be used to accommodate the service conduits and services connection with adjacent modules. The cuts in the bearer lead to structural capacity reductions of bearers which must be considered in the design stage. The proposed intra module connection method could boost factory fabrication of modules allowing faster jointing methods.

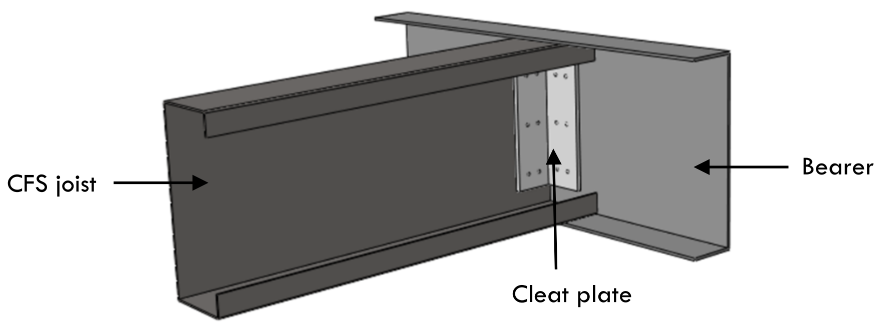
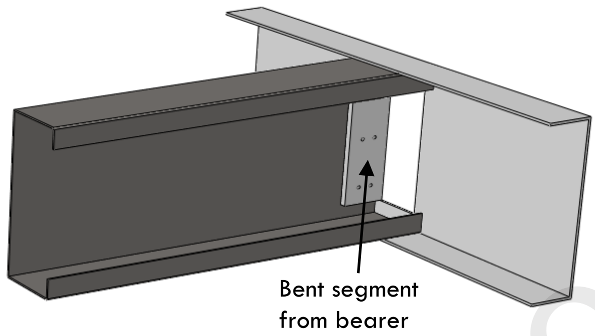
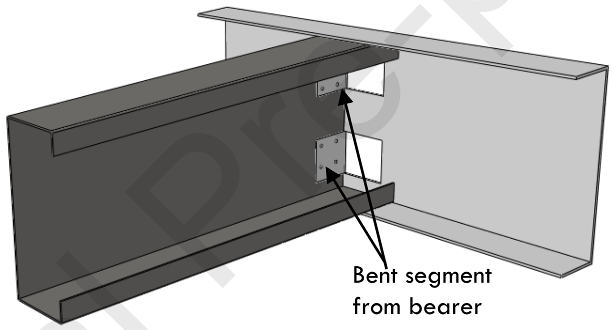


Fig. 20. Conventional cleat plate connection used in CFS frames



(a) Single cut-and-bend connection



(b) Double cut-and-bend connection

Fig. 21. New intra-module fast jointing connection method

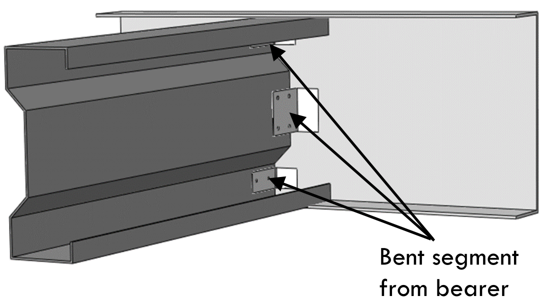


Fig. 22. New intra-module connection fast jointing method for sigma sections

4.6. Healthy modular building concept

The Recent covid-19 situation highlighted the need of healthy building concept in building design. This is an existing concept, however, now the implementation of this into buildings becomes more desirable. Recent experience from covid-19 has emphasised that people with unhealthy living and working conditions were prone to covid-19 disease. This statistic highlights the necessity of healthy building in the future with good air quality [74]. This is due to the fact that some people spend most of their time engaging in indoor activities. Thus, post covid-19 local manufacturing will be a challenge [51].

The healthy building concept not only should be standard for hospitals but also offices and living homes [29]. One of the major requirements is increased ventilation required to dilute airborne contaminants and to decrease the rate of disease transmission [75]. It has been identified that a low humidity environment suits the survival of viruses. The optimal range of humidity is 40-60% [75]. Therefore, the future modular building construction should focus on integrating technologies such as ventilation systems (clean air and displacement) and various filtration technologies [29]. For example, the modular building may consider adopting breathing walls as depicted in Fig. 23. This modular breathing wall could be employed as a non-load bearing wall in a corner post modular unit.

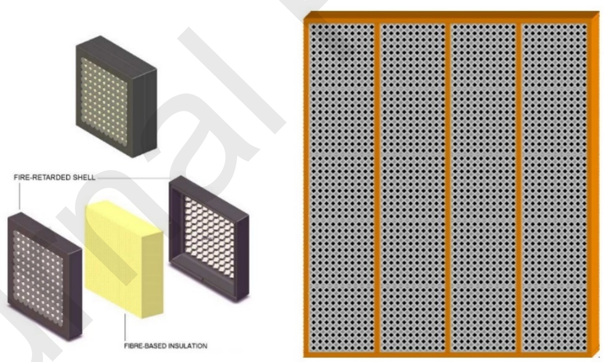


Fig. 23. Modular breathing panels [76]

The modular breathing panels is a convenient system composed of insulation media and casing. It has the capability of producing nearly zero U-value and distributing the air supply without any extra cost. Moreover, it is a lifetime air filtration package that could be easily adopted in steel-framed modular buildings[76]. It is also believed that post-covid-19 construction will focus on energy-efficient and greener methods [77].

5. Conceptual design of corner post modular unit for emergency situations

This paper focuses on developing a performance improved corner post modular system for emergency situations. Corner post-module is mainly considered as combining more than one modular unit that would lead to a large working area without any partition walls. Intermediate posts might be required for long-span modules. The robustness of the corner post modules solely relies on the corner posts as it carries and transfers the entire load of a module. 100 × 100 mm or 150 × 150 mm SHS sections are generally used for high-rise construction while 80 × 80 mm SHS may be employed in low-rise modular constructions [1]. The use of SHS hollow sections as corner posts is due to its high buckling resistance. The hollow steel columns are sometimes filled with light-weight concrete to maintain the same column size throughout each floor and avoiding higher thickness or larger column size at low floor levels [5]. This will help to use the same inter-module connections for the entire modular structure.

Fig.24 illustrates the conceptual design of the proposed modular unit which suits all purposes including health care emergencies. The optimum CFS beams are proposed to be employed as floor and ceiling joists. These optimum joists such as folded-flange and sigma sections can carry the same amount of load with up to 24% less weight. This results in a lightweight steel-framed modular unit. This lightweight modular unit could solve the weight-related challenges (transportation and lifting tower crane capacity) of modular construction.

The proposed corner post modular units include a simple and faster intra-module connection jointing method name cut and bend connection. This cut and bend connection method uses no additional material for connection because a portion of the web in the bearer is used as a connecting plate. The holes generated in bearers can be used to accommodate service conduits. This simple cut and bend intra-module connection method reduces the factory fabrication time of modules by this faster jointing method. Thus, for any emergency situations, modular units can be delivered at the required compacted timeline for hospital extensions and other needs.

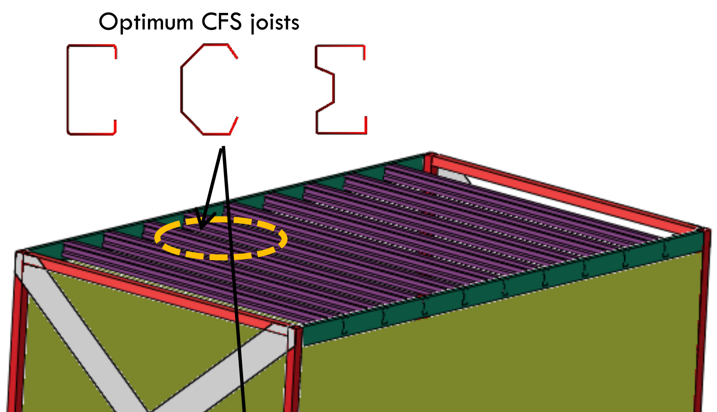


Fig. 24. Proposed corner post modular units for all application including health care emergencies

To ensure the lateral stability of the proposed system, strap bracing (X-bracing) is preferred over K- and other conventional bracing based on the recent experimental finding [72]. The experience from covid-19 pointed out that building an indoor environment should contain good air quality. Therefore, modular breathing panels are proposed as sidewall in corner post modular units. This will be a non-load bearing component as gravity load is transferred through corner post. The filtration media in modular breathing walls dilutes the airborne contaminants and reduces the rate of disease transmission. Therefore, the proposed corner post modular system provides a safer indoor environment and improved air quality for inhabitants.

The proposed affordable modular system for emergency situations like covid-19 has considered not only the health-related improvement but also improvement in structural, fire, and lightweight aspects. There therefore the proposed modular system will be a full package with enhanced overall performance.

6. Summary and conclusions

The recent covid-19 health care crisis has resulted in a surge in the requirement of health care infrastructures such as hospital extensions, testing centres, isolation units, and so on. However, these need to be delivered faster to treat patients and control the rapid spread of the disease. Modular construction methods have been widely practiced across the world to meet this requirement. A study on how the existing steel-framed modular units can be improved in terms of healthcare, structural, fire, lightweight, fast fabrication for the robust use in emergencies is investigated in this paper. Optimisation studies, FE analysis, experiment results, a survey on healthcare-related modular applications were used to further improve the steel-framed modular units. The following conclusion can be drawn from the investigation.

- Modular construction is the only potential solution to meet the urgent need for infrastructure compared to the conventional construction method. The wide use of modular construction across the world for health care infrastructure is evident for this.
- A novel optimisation method minimising the weight of the CFS joists (sigma and folded-flange section) without compromising the capacity resulted in up to 24% of weight reduction per meter length. The application of these sections will produce lightweight modular units without compromising structural performance.
- Based on the recent test finding, X-bracing (strap bracing) is preferred in steel-framed modular units over K- and other conventional bracing.
- The fire performance of steel-framed modular units can be improved using staggered slotted perforation is CFS joists. This controls the heat transfer through the panels by making the heat transfer path complex.
- Simple cut and bend intra-module connection is a viable jointing technique for the quick fabrication of steel-framed modular units. This kind of technique is required to deliver modular units within a shorter period at any emergency situations.
- The modular breathing panels are a potential solution to be introduced in steel-framed modular units to maintain the improved indoor air quality and to reduce the spread of disease. This ensures a healthy modular unit.
- The proposed modular building system is proven to be suitable for ongoing crisis and post-crisis building requirements with enhanced overall performance. The future works focus on full scale experimental and numerical investigation of the proposed modular unit.

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Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: