ICSESM2019-86

OPTIMISED AND SLOTTED COLD-FORMED STEEL CHANNELS: A SOLUTION FOR MODULAR BUILDING SYSTEMS

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Abstract: The steel construction industry has recently put a lot of effort to better understand Modular Building Systems (MBS) and replaced, where possible, conventional construction methods. MBS claims promising advantages including speed of erection, improved quality, reduced cost, and flexibility. Therefore, research efforts are tuned to the structural, social, and safety evaluations of MBS while it is recognised that there are challenges associated with their use, yet to be addressed. The main challenges are improving structural, fire, and energy performances, need for lightweight materials, more access space during renovation and transportation difficulties. This paper investigates how the use of optimised Cold-Formed Steel (CFS) members with slotted web can address such challenges. The optimisation was performed using Particle Swarm Optimisation (PSO) method and subsequently, slotted perforations were added to enhance the structural, fire and energy performances, respectively. Finite Element (FE) analysis was employed to assess the performance of optimised innovative CFS beams with slotted perforations. As a result, the optimisation and FE analyses resulted in a 30-65% of flexural capacity enhancements along with notable performance improvement in fire and energy performances over conventional Lipped Channel Beam (LCB). Using such optimised innovative sections, a conceptual design of a corner-post module was also developed. Hence, the optimised CFS channels with slotted perforations would be a convenient tool to overcome the reported challenges related to MBS, result in more cost-effective and efficient building solutions.

Keywords: Modular construction and challenges; Cold-formed steel; Innovative optimised sections; Finite element analyses; Conceptual design.

1. Introduction

Modular construction, often termed as off-site construction, is mainly a factory-based construction method where individual modules are constructed off-site and promotes assembling the modules on-site. Thus, more than 75 % of the construction phase is completed off-site resulting shorter project duration, improved quality, and sustainability, as well as reduces cost and waste generation (Lawson, Ogden and Bergin, 2012). Figure 1 depicts how the module is transported and assembled in the factory. However, recent research studies (Navaratnam et al., 2019, Liew, Chua and Dai, 2019, Ferdous et al., 2019 and Lacey et al., 2018) have investigated the structural, social and economic performances of MBS and revealed that there are still challenges associated with their use. The major reported challenges are the need for enhanced structural, fire and energy performances, need of lightweight materials and high-performance materials and limitations in road restrictions during transportation, connection methods, lifting of modules, design guidelines, and accessibility during refurbishment works.

To date, many research studies have investigated shear (Keerthan and Mahendran 2013a, 2013b, 2015a and 2015b) and web crippling (Sundararajah et al, 2017a and 2017b) behaviour of conventional CFS sections. Extensive research on innovative hollow flange sections (Keerthan et al, 2014, Keerthan and Mahendran, 2012 and Mahendran and Keerthan, 2013) were also performed. However, these sections were not subjected to optimisation. Optimisation framework plays a vital role as it offers enhanced structural performance compared to the available conventional CFS sections with the same amount of material, thus lower carbon footprint. In addition to that optimisation technique, it results in substantial amount of material saving leading to more sustainable construction. Recent studies (Ye et al., 2016 and Gatheeshgar et al., 2019b) used Particle Swarm Optimisation (PSO) technique for the structural optimisation of CFS beams. Moreover, Degtyareva et al. (2019) highlighted that thermal performance of the CFS beams can be amplified by incorporating slotted perforations to the web. However, this option can negatively affect the load-bearing capacity of CFS beams. Incorporating slotted perforations to the optimised novel channels would enhance the overall performance. A limited investigation has been performed related to employing slotted perforated optimised CFS beams for MBS.

This paper presents an investigation of employing optimised CFS beams with slotted perforations for MBS and explores their potential in addressing some of the aforementioned challenges. CFS beams were optimised using PSO for the enhancement of structural performance. FE models of optimised novel CFS beams were developed based on the validation process and used to assess the structural performance of the CFS beam with slotted perforations. A conceptual design of a corner-post module was also developed using the proposed novel optimised CFS beams.

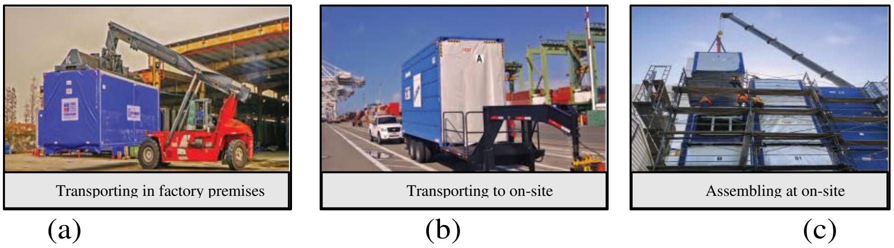


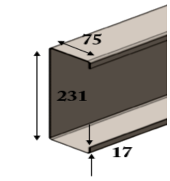
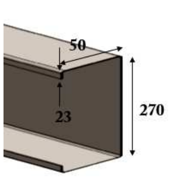
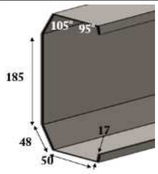
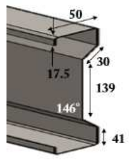
Figure 1: Module transporting and assemble phases (Panoramic.com, 2019)

2. Optimised CFS novel sections

This section briefly summarises the performed optimisation framework. In this comparative study, three optimised sections were considered. A commercially available benchmark lipped channel beam (LCB) is also considered to compare the structural performance of the optimised sections. This benchmark LCB section has the cross-section properties of 415 mm coil length and 1.5 mm thickness, and mechanical properties of 210 GPa modulus of elasticity, 450 MPa yield strength, and 0.3 Pois-son's ratio. It should be noted that during the optimisation, the aforementioned properties were main-tained constant, thus all the optimisation sections also have the same properties. LCB, folded-flange and super-sigma sections were considered for the optimisation and the optimisation was performed using the PSO algorithm (see Table 1). Ye et al. (2016) and Gatheeshgar et al. (2019b) successfully used this PSO algorithm for the structural optimisation of CFS beams.

First section moment capacity equations of the considered CFS beams were developed based on the EN1993-1-3 and incorporated into the optimisation algorithm which was developed in MATLAB. The objective of the optimisation problem was set to maximise the flexural capacity of CFS beams and the theoretical and manufacturing constraints were set as the lower and upper bound. The extensive details on optimisation procedure can be found elsewhere (Ye et al., 2016 and Gatheeshgar et al., 2019b). The optimised sections were then analysed with advanced FE analysis.

Table 1: Optimised dimensions and bending capacities of the considered CFS beams

CFS beams	LCB Benchmark	LCB Optimised	Folded-Flange	Super-Sigma
Optimised dimen-sions				
Bending Capacity (kNm)	10.30	13.38	16.12	17.43

3. Non-linear finite element analysis

The optimised CFS beams were analysed with an advanced FE method in order to investigate the flexural behaviour in an extensive manner. A commercially available general-purpose FE software package, ABAQUS version 2017, was employed. FE models of the four prototypes were developed as simply supported four-point loading set-up with a total span of 3500 mm and mid-span of 500 mm. This set-up ensures the pure bending failure at the mid-span due to the absence of the shear stress.

3.1 FE modelling

Brief information on FE model development is presented in Table 2. This includes the element type, mesh refinement, boundary conditions, and geometric imperfections. The developed FE models were subjected to two methods of analysis: linear buckling analysis and non-linear static analysis. Linear buckling analysis was performed to generate the imperfection shape and magnitude. The lowest buckling mode was selected to superimpose the initial geometric imperfection of the CFS beams. Non-linear static analysis was used to analyse the bending behaviour of FE models accommodating material yielding and large deformations.

Table 2: FE model description

Model characteristics	Brief description
Loading method	Displacement control loading at two middle supports
Material Model	Elastic-perfectly plastic models: CFS has negligible strain hardening and adopting strain hardening results in a minimal effect on capacity (Keerthan and Mahendran, 2011)
Residual stresses	Residual stresses and corner enhancement counter effects each other, therefore not considered in the analysis
Element type	S4R shell element – To capture the non-linear behaviour
Mesh refinement	Flat segments – 5mm × 5 mm mesh, corners - 1mm × 5 mm and slotted perforated regions-1.5mm × 5 mm
Geometric imperfections	Initial imperfection magnitude of d/150 was used, where d=web height. *IMPERFECTION option available in ABAQUS was used to introduce the imperfection shape and magnitude (Keerthan and Mahendran, 2014).
Straps	Straps were simulated as boundary conditions and uniformly distributed at 250 mm intervals at top and bottom flanges

3.2 Verification of the FE models

The FE models of LCBs and Sigma sections were developed and validated against the experimental results reported in Pham and Hancock (2013) and Wang and Young (2014), respectively. It is noteworthy to mention that web side plates were simulated as coupling constraints where all the translations and rotations were coupled to the reference point (shear centre). Table 3 provides the validation results of the LCB and Sigma sections with experimental data.

Table 3: Validation of the bending models with experimental results

Specimen		M_{Test} (kNm)	M_{FE} (kNm)	M_{Test}/M_{FE}
Pham and Hancock (2013)	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 (2014)	C-0.48-B4	1.02	1.07	0.95
	C-1.0-B4	2.99	3.31	0.90
Mean				0.96
COV				0.062

Overall, validation process resulted in a mean value of 0.96 and coefficient of variation value of 0.062. The failure mode and load-displacement behaviour comparison between the test and FE model of C20015 is depicted in Figure 2. These satisfactory agreements obtained in the validation process confirm the accuracy of the FE model characteristics for further study.

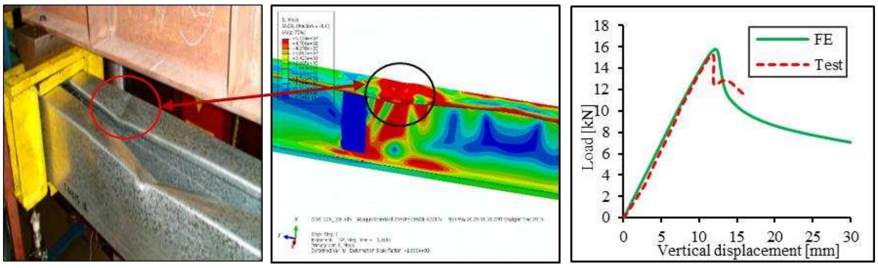


Figure 2: Comparison of the failure mode and load-displacement behaviour for C20015 (Pham and Hancock, 2013) with FE results.

3.3 Flexural performance of the optimised sections

The FE models of the optimised CFS sections were developed based on the validation process to investigate the flexural behaviour. A similar model characteristic used in the validation process was adopted to construct the FE models of LCB benchmark, LCB optimised, folded-flange and super-sigma CFS beams. Figure 3 depicts the bending failure modes of the super-sigma section at different stages observed from the non-linear FE analysis and as expected the failure occurred within the pure bending zone. This confirms the resulting capacity is the section moment capacity of the CFS sections. The section moment capacities obtained from the FE analysis were then compared with the section moment capacity prediction from the EN1993-1-3. Table 4 presents the comparison of the section moment capacities between the FE models and EN1993-1-3.

The result gives a mean and COV values of 1.00 and 0.022, respectively, thus confirms the accuracy of the optimisation process. In addition, Table 4 presents the bending capacity enhancements of the optimised CFS sections in terms of percentage by taking the benchmark section as the reference. The results reveal that super-sigma section is capable of resist 65% higher flexural capacity over the benchmark section with the same amount of material. This is due to the intermediate web stiffeners in the super-sigma section and the optimum dimensions achieved from the optimisation framework. Moreover, sigma sections naturally have the shear centre closer to the outer web, thus minimised the torsional failure due to eccentric loading. This adds more value to the super-sigma section to employ in MBS.

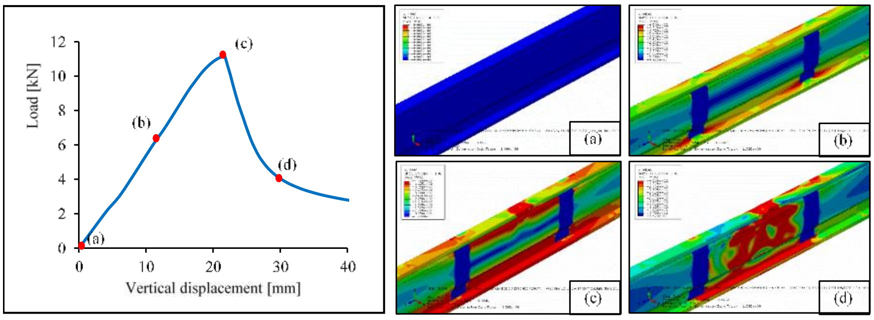


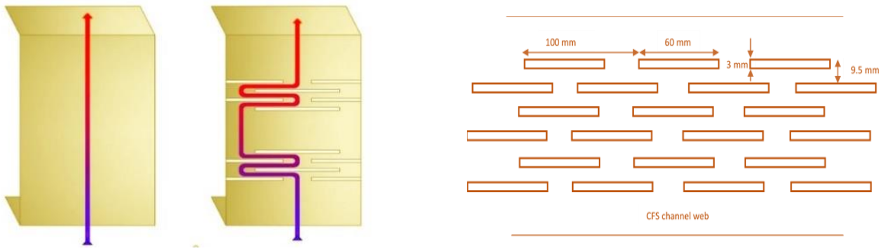
Figure 3: Bending failure mode of super-sigma section at different stages

Table 4: Comparison of the bending capacity predictions from FE analysis and EN1993-1-3 (EC3)

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
Mean					1.00
COV					0.022

3.4 Flexural performance of the optimised sections with slotted perforations

The thermal performance of CFS channels can be amplified by incorporating the slotted perforations in the web (Degtyareva et al., 2019). This becomes possible as the slotted perforations increase the thermal transmittance path as shown in Figure 4a. However, these slotted perforations can reduce the load-bearing capacity of the CFS beams due to the material reduction in the web. In general, the reduction of the bending capacity due to the large web openings is about 25%. Since the optimised sections have the maximum bending capacity enhancement of 65%, accommodating web openings still results in enhancements. Therefore, slotted perforations were used with the optimised CFS beams to experience both enhancements of structural and thermal performance. The degree of the reduction of the bending capacity of the optimised CFS beams with the inclusion of slotted perforations was investigated through FE analysis. The slotted perforation configuration used in this study is depicted in Figure 4b. Figure 5 shows the overall results of the FE analysis.



(a) Heat transfer path (b) Slotted perforation pattern

Figure 4: Slotted perforated CFS beams

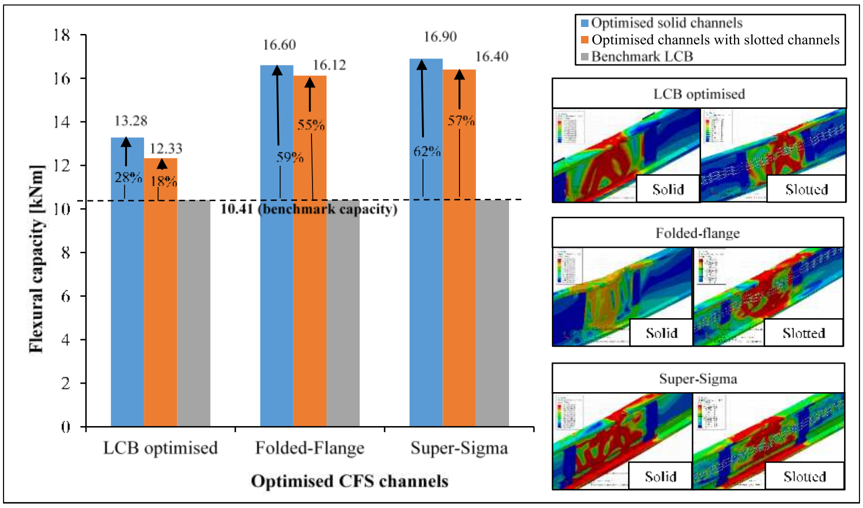


Figure 5: Bending behaviour of the optimised CFS beams and Optimised CFS beams utilised with slotted perforations.

The FE results showed that for all the optimised sections, less than 10% of the bending capacity is reduced. To elaborate, 18%, 55% and 57% of bending capacity enhancements were achieved for the optimised LCB, folded-flange, and super-sigma CFS beams, respectively despite the inclusion of the slotted perforation compare to the benchmark section without slotted perforations. Figure 5 also depicts the failure mode comparison between the optimised CFS beams and optimised CFS beams with slotted perforations. Therefore, including slotted perforations to the optimised sections would result in enhanced bending capacity. In addition, slotted perforated channels have enhanced thermal performance (Degtyareva et al, 2019). Details on how these optimised CFS channels with slotted perforations can address the MBS challenges are described in the following sections.

4. MBS challenges and solutions

4.1 Structural efficiency

Even though MBS has an easy installation procedure, it has complex structural arrangements. Since the MBS uses non-conventional connection methods (inter-module connection, intra-module connection, and module to foundation connections), the load transferring mechanism in MBS cannot be easily understood (Navaratnam et al., 2019). In addition, there is limited research which studies 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 conditions. The optimised CFS beams are suitable to address this challenge as they have up to 65% of flexural capacity enhancement.

4.2 Fire resistance and energy performance

Nowadays, more attention is paid towards fire safety of buildings after the detrimental fire accident occurred at Grenfell Tower, London, UK in 2017. Webs in CFS beams are often exposed to fire and temperature rises in webs which 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. 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.

4.3 Lightweight materials (Transportation and lifting capacity of the tower crane limitations)

Lacey et al. (2018) and Liew et al. (2019) 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. CFS components can be replaced, easily reassembled and have no long term issues such as durability, creep and shrinkage. 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.

The resulting lightweight modules can meet the challenges of transportation limitations and the lifting capacity of the tower crane. Usually, the weight of a steel modular unit is about around 20 t. Some roads and bridges have weight limitations; in particular there are bridges with weight limits below 20 t which complicates the module transportation phase and can increase the energy consumption in the life cycle assessment exercise. Liew et al. (2019) claim a 60% cost increment for the tower crane is resulted, when lifting weights beyond 20 t. The use of optimised CFS sections in MBS can significantly solve these issues as it ensures lightweight module.

4.4 Access requirements

Ferdous et al. (2019) and Lacey et al. (2018) 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. Such enhanced spacing between the members could address the problem of the limited access in MBS.

Consequently, utilising MBS with optimised Super-Sigma sections can address some of the identified challenges. Moreover, these optimised Super-Sigma sections can be employed as purlins and rafters in light gauge steel constructions.

5. Conceptual design of modular buildings using optimised CFS beams

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 more economical and efficient design solutions. Lawson (2007) illustrated the arrangements of the structural elements in a corner post-module constructed with conventional LCB sections. Gatheeshgar et al. (2019a) proposed a conceptual design of corner post-module using the hollow flange beams. Since Super-Sigma sections with slotted perforations have been identified as a good alternative to benchmark LCB in terms of structural, fire and thermal performances, the proposed MBS will be designed with Super-Sigma sections (ceiling and floor joists) as shown in Figure 6.

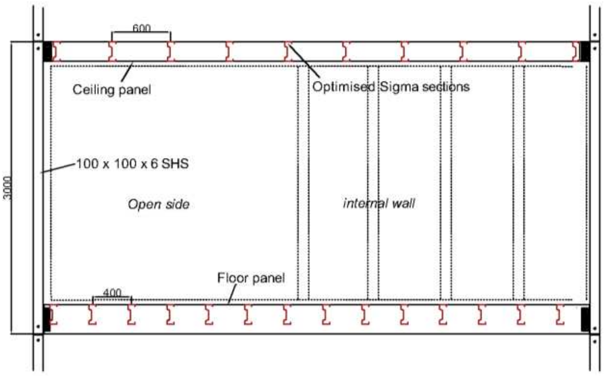


Figure 6: Conceptual layout of corner post-module employed with slotted perforated Super-Sigma sections

6. Concluding Remarks

This research proposes to employ the optimised CFS sections with slotted perforations into MBS to improve the 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 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 for additional lateral restrains in order to prevent the twisting effect. Furthermore, 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.

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

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