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**Conference Paper** · June 2019

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NORDIC STEEL 2019
The 14th Nordic Steel Construction Conference,
September 18–20, 2019, Copenhagen, Denmark

# Modular Building Design: Post-Brexit Housing

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## ABSTRACT

The use of modular building systems (MBSs) in the construction sector is increasing. MBSs enhance structural performance of buildings, quality control, and construction speed than traditional methods at a lower cost. Additional benefits can be associated with resource efficiency at both the production and construction phases, which may increase MBSs' attractiveness and popularity in the short- and long-term future. In the UK, the government is planning to solve Britain's housing crisis by constructing more than 100,000 modular homes in an effort to meet its target to provide a million new homes by 2020. At the same time, the construction sector is facing post-Brexit skills shortages, while it is undergoing a technological revolution. One outcome of the latter has been the production of cold-formed steel (CFS) hollow flange sections, which can be optimised using genetic algorithm and finite element analyses in order to improve the load-carrying capacity of modular buildings. These optimised CFS beams, employed in MBSs, can light gauge the frame building constructions. This paper presents a review of MBSs and the application of CFS hollow flange steel sections in construction. It then summarises some of the key outputs of numerical studies on the structural behaviour of hollow flange beams to justify its applicability in MBS.

**Keywords:** Cold-formed Steel Beams, Modular Building, Britain's Housing Crisis, Finite Element Analysis, Bending, Shear and Web Crippling.

## 1 INTRODUCTION

Britain is to experience a new wave of construction, as the UK government plans to build 100,000 modular homes in order to solve the housing crisis by 2020. Concurrently, advancements in innovative construction technologies have given rise to the rapid increase in the automated, off-site modular building system. MBSs, shown in *Fig.1*, can deliver 40% lighter weight, allow for higher quality and precision in the manufacturing stage, allow better quality control, speedier construction and installation compared to traditional methods (e.g. 6 months quicker), enhanced structural performance, a lower cost (e.g. net savings in the order of '000s to '000000s), and improved resource efficiency (1-5). MBSs are widely used in low-rise residential buildings, as well as in other buildings of different functional purposes, such as educational structures, health care facilities and other commercial buildings. Most recently, MBS have also been introduced in multi-storey and mixed-use (commercial with housing) buildings, and even in high-rise construction (1).

https://doi.org/10.1002/cepa.1160

Infrastructure and Projects Authority (IPA) (6) acknowledged that “the construction sector faces issues such as low-profit margins and lagging productivity compared to other sectors of the economy” and committed to tackling this in several ways, including “accelerating the use of modern methods of construction like off-site manufacturing”. Hence there is a need to develop a cost-effective modular building system with enhanced structural performance to solve Britain’s housing crisis. CFS has increasingly been used in low- and medium-rise buildings with a rise in the use of standardised MBSs. These CFS elements can be optimised to improve the load-carrying capacity of the element.

This paper presents a review of modular buildings systems and applications of CFS hollow flange steel sections in modular building framework and numerical studies on the structural behaviour of hollow flange beams.

*Fig. 1.* Modular Building Systems (7)

## 2 MODULAR BUILDING SYSTEMS (MBS)

The construction industry faces significant challenges and MBS have the potential to address most of these challenges (6). MBS is a term used to describe the rapid construction of buildings by the use of advanced technologies whereby structural components are manufactured off-site and the construction site is used only for assembling. Off-site manufacture (OSM) is a modern method of construction or smart construction, defined as “the design, planning, manufacture, and pre-assembly of construction elements or components in a factory environment prior to installation on-site at their intended, final location” (6). It combines various technologies the basic principle of which is to allow a rapid construction on-site.

The concept of OSM, which is often known as ‘light’ and modular systems, has brought improvements to the construction sector, with benefits such as adaptability to the variable demands of the market and contextual situations, and ease of assembly. Additional benefits of off-site construction include: cost reductions in project construction and maintenance over the lifetime of the building; on-time and on-budget delivery of the project to the required quality standard, reducing contractual risk for the client/public sector and improving satisfaction; enhanced project management, with improvements in profitability and productivity of contractors, safety of the working environment and resource efficiency (1, 5).

Resource efficiency is particularly important form the sustainability point of view. In construction, resource efficiency and waste can be attributed to, and therefore managed appropriately at, each stage of the construction process i.e. design, manufacture, on-site, operation, refurbishment and demolition (8). MBSs allow construction sector to gain control of the resources used in the production phase, and reduce waste at all stages of the construction process, from production through to use and end-of-life management. Modular buildings can be repaired during their use, retaining as such their functional purpose for longer, while they can dismantled and re-used if they are no longer needed, thereby effectively maintaining their asset value over their lifetime (9). These practices not only can improve profitability and productivity in the construction sector, but can also have a reduced impact on the environment, economy and society improving as such sustainability in the construction sector.

MBSs offer a new, modern approach to construction that can attract, retain and inspire a new generation of workers. It can be a solution to the current hosing crisis problem in UK. It is envisioned that more customers will be turning to MBSs once they become more reputable in terms of their time saving advantages, resource efficiency and inherently greener credentials involved. Therefore, there is a need to develop cost-effective MBS with enhanced structural performance to solve Britain's housing crisis. The aforementioned two characteristics can be achieved by incorporating optimised CFS elements in MBS.

## 3 NUMERICAL ANALYSIS

Modelling the CFS sections is a heavily non-linear problem with both material and geometrical non-linearities, and it was performed using ABAQUS version 2017 in order to evaluate the flexural, shear and web crippling behaviours. S4R elements having a mesh size of 5 mm × 5 mm and centreline dimensions were used to construct the model. A perfect plasticity model was adopted in all developed FE model due to the negligible strain hardening in CFS (10). The geometrical imperfections were treated with eigen value buckling analysis and the magnitude was a function of clear web height, $0.006d_1$ (11). The imperfection shape was introduced using *IMPERFECTION option in ABAQUS. Hollow flange beams were optimised using a genetic algorithm (GA). The optimisation was executed maintaining the amount of material constant (coil length=415 mm, thickness=1.5 mm, Grade 450 MPa). Each optimised sections capacities were compared with benchmark lipped channel beam (LCB) section (see *Fig. 2).*

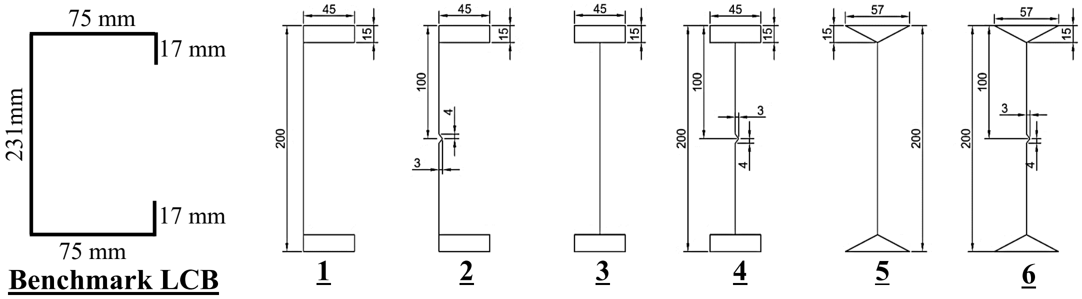
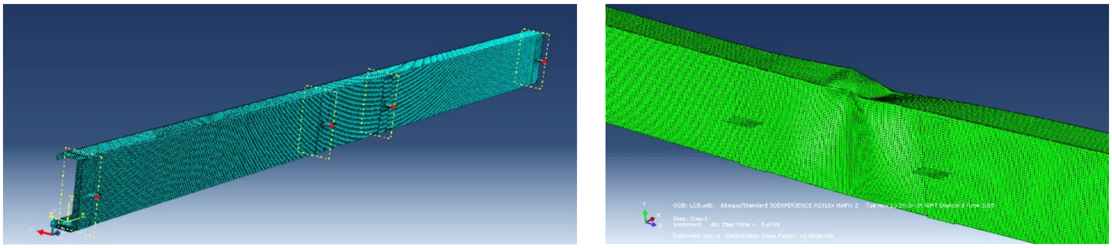


*Fig. 2.* Optimised Hollow Flange Beams

### 3.1 Bending

The modelled beam was tested under four-point loading so that the failure will occur within the constant moment region in the middle span. Shear centre loading was applied through a deflection acting through the two central web plate and simply supported boundary conditions were implemented (*see Table 1*). These web plates were attached to the prototype using tie constrains option in ABAQUS. Past experimental studies showed that strap failures did not arise, hence, straps were simulated using suitable boundary conditions in the top and bottom flanges. *Fig. 3* illustrates the failure modes of developed FE models.



a) b)

*Fig. 3.* Bending FE failure mode: Benchmark LCB a) Mesh; b) Post bending failure

*Table 1.* Boundary conditions for Bending FE model

| Boundary condition | $UT_x$ | $UT_y$ | $UT_z$ | $UR_x$ | $UR_y$ | $UR_z$ |
|---|---|---|---|---|---|---|
| Pin | R | R | R | F | F | R |
| Roller | R | R | F | F | F | R |
| Straps | R | F | F | F | F | R |

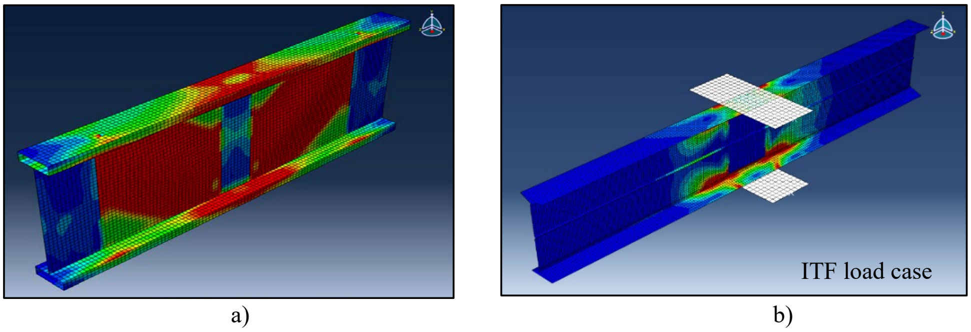
Note: Here R denotes the 'restrain' and F denotes the 'free' boundary conditions

### 3.2 Shear

The prototypes were tested under three-pint loading; the length was determined by the clear web height, with aspect ratio 1.0 in order to ensure pure shear failure. Simply supported boundary conditions were applied to the edge of the web plates to avoid torsional effects (see *Table 1*). The load was applied as providing displacement to the middle web plate. Geometrical imperfections were incorporated to the non-linear analysis via eigen vector field approach as stated previously. The dynamic explicit option was used for the analysis. Details of developing FE models for shear failure can be found elsewhere (12, 13). *Fig 4a* shows the failure mode of prototype 3.

### 3.3 Web crippling

Web crippling was modelled under interior two flange loading conditions (ITF). The sections' overall depth were defined by a function of depth, 5d and the loading was applied through 100 mm bearing plates which were assigned as R3D4 rigid elements. Since the folding radius hugely controls the web crippling behaviour, 1 mm × 5 mm mesh size was incorporated for corner regions only. A quasi-static analysis was used to overcome the contact difficulties faced in the non-linear static analysis. Moreover, the bearing plates were connected to the beam using surface-to-surface, 'hard' contact model option available in ABAQUS with a coefficient of friction of 0.4. The loading plate at the top was assigned as displacement control to ensure smooth loading. The range of detail on (14) was followed to generate FE models for web crippling behaviour. *Fig 4b* shows the FE model prototype for web crippling.



a) b)

*Fig. 4.* Failure modes a) Shear (prototype 3); b) Web crippling (prototype 6)

### 3.4 Results and discussion

The results obtained from the FE analyses using ABAQUS software are summarised in *Table 2,* which covers all prototypes and its capacities when subject to flexure, shear and web crippling actions along with percentage comparisons to the industry standard LCB.

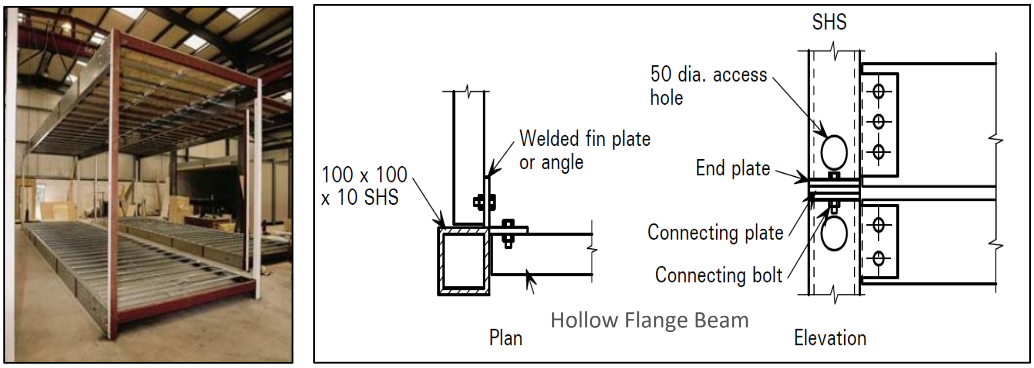
The obtained results are favourable, showing massive improvement in capacities over standard LCB section. Finite element results showed (*see Table 2*) that for the same amount of material, hollow flange beams (Prototypes 1 to 6) leads to a higher flexural capacity, which is around 65% to 90% higher than a standard commercially available channel section. Hollow flange beams are also easy to connect to typical floor systems and modular building systems, thus, are suitable for practical CFS beam sections. It was found that the shear and web crippling capacities of hollow flange beams were not reduced when compared with standard commercially available channel section.

*Table 2.* Finite element analysis results of hollow flange sections

| Section shape | Flexure Capacity Ms/(kNm) | Ms (%) | Shear Capacity Vv/(kN) | Vv (%) | Web Crippling Capacity Rb/(kN) | Rb (%) |
|---|---|---|---|---|---|---|
| LCB (standard) | 11.23 | 100% | 53.70 | 100% | 11.12 | 100% |
| 1 | 18.73 | 167% | 53.74 | 108% | 33.09 | 298% |
| 2 | 18.89 | 168% | 59.56 | 111% | 33.16 | 298% |
| 3 | 20.10 | 179% | 55.46 | 103% | 21.59 | 194% |
| 4 | 20.30 | 181% | 56.31 | 105% | 21.64 | 195% |
| 5 | 18.55 | 165% | 60.67 | 113% | 28.97 | 261% |
| 6 | 21.66 | 193% | 61.21 | 114% | 28.98 | 261% |

## 4 CONCEPTUAL MODULAR BUILDING DESIGN

Proposed modular building systems will be designed to provide fully open sides by transferring loads through the longitudinal edge beams (Hollow flange beams) to the corner posts (SHS) (see *Fig. 6*). The proposed framework of the module is employing cold-formed steel members, such as Square Hollow Section (SHS) columns and hollow flange 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 storeys 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. 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. *Fig 6a* shows the corner-supported modular building system while *Fig 6b* presents the modular building connections. Further research on modular building connections, structural tests and advanced finite element models of modular building systems are in progress.



a) b)

*Fig. 6.* Modular building design a) Corner post module; b) Connections (Corner post-MBS) (7)

## 5 CONCLUSIONS

The construction sector is facing significant challenges associated with low productivity, poor performance and skills shortage, lack of information/data management relating to structures life cycle maintenance and costing, and resource efficiency, which may be even more significant after Brexit. Therefore, there is a strong need to develop cost-effective modular building systems with enhanced structural performance to solve Britain's housing crisis, improve construction sector's productivity and sustainability overall. This paper provides a review of modular buildings systems and applications of cold-formed hollow flange steel sections in modular building systems and numerical studies on the structural behaviour of hollow flange beams. It was found that the same amount of material, hollow flange beams (Prototypes 1 to 6) can lead to a higher flexural capacity, around 65 to 90% higher, than the standard commercially available channel section. Such hollow flange beams are therefore, proposed to be used in light gauge steel frameworks and modular building systems in order to enhance the structural performance.

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