Multi-storey Modular Cold-Formed Steel Building in Hong Kong: Challenges & Opportunities

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Abstract. Modular building construction has become widely popular across the continents, such as in America, Europe (United Kingdom), Asia (Singapore), and more recently in Australia. Promoting sustainability in construction, the application of modular construction has been successfully implemented in very broad range building functionalities. These include student residences, private housings, hotels, commercial buildings, military accommodation, health facilities, as well as other services units attached to the main buildings. Several low-rise buildings (6 to 10 stories) as well as high-rise buildings (20 to 30 stories) have used this type prefabricated off-site building system as an alternative construction method. Among those existing projects, modular steel building brings significant advantage on the manufacturing process and erection speed. These will be beneficial for Hong Kong which has very high pressure on housing demands. Due to its excellence on strength and durability, the modular integrated construction (MiC) in Hong Kong is looking to the direction of using cold-formed steel as structural component. Some challenges and opportunities are exist and these will be discussed in this paper.

1. Introduction
A modular building is constructed from stacks of building blocks. The blocks are fabricated in the workshop and they are delivered to the site as a 3D volumetric module [1]. Each module is assembled by prefabricated elements, such as floors, walls, roofs, mechanical services, and electrical fittings. Together with structural elements, one module may contain single unit or even more than one unit [2]. By obtaining 3D volumetric buildings, it will minimize the amount of on-site works such as large volume of concrete casting, steel erections, and major architectural and installation works [3]. Moreover, modular volumetric building is also suitable for projects which has limited construction space.

Among the existing construction material, steel structure gives relatively more benefit on this prefabricated off-site construction technique. The primary advantage of modular steel building is on the weight and flexibility which ease manufacturing process such that enhance the construction speed [4]. Technical issues and challenges together with proposed solutions along modular steel building fabricated by hot-rolled sections have been assessed in the technical note [5]. Nevertheless, there are some questions remaining on the durability (corrosive resistance and fire resistance) on this steel type.
Despite the positive future opportunities, much wider technical challenges on application of modular construction technology have been realized [2, 6]. There are still lack of confident on the structural behavior due to an inadequate design and construction guidelines as well as code requirements. Moreover, promoting of cold-formed steel as an alternative main structural element is remain scarce. Under the extreme loads, particularly very huge wind loads as in Hong Kong, the performance of modular building construction has been questioned. Nevertheless, there have been many studies on the performance and behavior of existing modular building structure. Those studies are summarized in the following section.

2. Literature Review on Modular Steel Building

The existing literatures provide examples on the practical structure design approach of the existing modular steel buildings. Due to lack of practical design codes on such type of structure, experimental and numerical tests have been conducted to assess the suitability and reliability of proposed system. Those existing studies confirm the promising performance of steel structure for modular integrated construction (MiC). Nonetheless, the studies have not been expanded to use cold-formed steel as primary structural elements.

Several tests of curtain wall structures from cold-formed steel acting as gravity load bearing element were conducted [7]. This was to investigate the possibility of secondary elements worked as primary structural element. It was shown from the tests if the composite action between wall board and its supporting structure would significantly increase the capacity of curtain wall structure. This technique was assessed for the application into high-rise building. Apart from that element test, the robustness of current practice for stability design method on steel structure from the BS 5950 was comprehensively observed. Several practical analytic approach for design recommendations to improve the design codes (BS 5950) were included. However, member imperfections that are associated with advanced analysis method have not been initiated.

Several case studies for success story of high-rise modular building construction projects in London were presented [3]. There were 3 case studies involved: 12-, 17-, and 25-story modular steel buildings. As the building heights were increased, concrete core wall was introduced as lateral force resisting system. This wall increased the overall structural stiffness such that building displacement due to wind loads can be controlled to meet a standard code [8]. Although the steel structure only carried the gravitation loadings, such reliable steel to concrete connection was capable to transfer the lateral loads to the concrete wall and to accommodate differential settlement that possibly arises [1]. Understanding on this mutual system, further study to dual cold-formed steel and concrete wall system is necessary.

Under an extreme loading, such as an earthquake, there have been some numerical studies performed [9, 10]. More recent study [11] focused on the behavior of 4-story building stabilized by concentric bracings. Detail regarding modelling approach of the bracing, vertical and horizontal connection between modules were evaluated. From the Incremental Dynamic Analysis (IDA) and Pushover Analysis, the simplification of such elements was verified and having consistent performance. Those studies have not seen a cold-formed steel as an alternative steel construction material.

As an additional alternative of structural system in a multi-story building, [12] propose an innovative flexible solution system using prefabricated modules. Rather than using dual system in [3], 100 mm concrete walls were spread out in both horizontal directions and along the building height provided as a stability element. This study proved that dual action between concrete walls attached to modular steel frames promoted flexible design of floor/room layout. However, the applicability for tall buildings is to be evaluated by further research. Another possible solution for modular high rise buildings is to use composite steel structure [4]. Using this composite action, it will also give benefit to the use of cold-formed steel. Nevertheless, this alternate composite system shall be investigated further.

Some extensive reviews of the past studies on the modular steel buildings have been provided
Those cover the experimental investigations on component materials, connection systems, and other pertinent structural design aspects. From the last literatures, it is concluded that none of studies have involved cold-formed steel as main element to carry the structural imposed loads.

3. Alternative Modular Steel Building Systems

In general, there are 2 alternatives construction material conventionally used: concrete and steel. So far, modular steel building was formed by hot-rolled steel sections for main structural frame. Cold-formed steel sections dominate the non-structural element such as façade support, ceiling supports, and curtain walls. Using cold-formed steel as main structural element has not been explored. The advantages and disadvantages of using hot-rolled steel and cold-formed steel will be discussed in later chapter.

Based on [5], the types of steel modules can be classified into two categories which depends on how gravity loads will be transferred to the foundation:

- Continuously supported modules
- Corner supported modules

On those two types, only discussion about the vertical and lateral force resisting system will be presented. More details related with the manufacturing process, optional module sizes, accessories components, and construction strategies can be referred to [1, 5].

3.1. Continuously Supported Modules

This type is also known as 4-sided modules. The modules will be manufactured from a series of 2D-elements in form of panels. The fabrication process starts from floor cassette and then covers by curtain walls and ceiling panels. These curtain walls are designated to transfer the gravity loads in a module to the foundation. It is so-called load bearing wall system. An investigation of the capacity of vertical post of the wall elements due to stiffening effect of the enclosure board of the wall has been studied [7].

This module is also applicable for “partially open-sided” modules. Special attention should be addressed on the wall openings due to some windows and doors necessary. The openings will create disruption on the load transfer process. Lintel beams and columns around the opening shall be designed for structural elements. The structural elements of this 4-sided module are illustrated in Figure 1.

![Figure 1. Typical structural view of 4-sided module (Image courtesy of Kingspan Off Site and Modular UK)](Image courtesy of Kingspan Off Site and Modular UK)
The stability of each module is provided by the vertical bracing along the wall and in-plane bracing under the floor cassette. The in-plane bracing acts as a floor diaphragm to transfer the lateral load in the building into vertical bracings. The module to module connection will assist the load transfer mechanism in addition to maintain structural integrity. Furthermore, the vertical bracing will capture the load and bring it to the foundation.

For low-rise buildings (6 to 10 stories height), the group of vertical bracings on several modules along the building perimeter can be relied as lateral force resisting element of the whole building. However, a reinforced concrete wall greatly improves the building stability in addition to vertical bracing in the modules of tall building [3]. In order to activate the concrete wall, the corner module adjacent to the concrete wall shall be tied together. This connection must also consider a differential settlement between the core wall and steel modules.

3.2. Corner Supported Module
The corner supported module, which is also applicable for open-sided module, still relies on the hot-rolled steel frame. The frame works as primary vertical force resisting element and it provides stability of each module. Depending on the beam span, it is useful if an intermediate column is added to minimize the steel beam and corner column size. A picture of open-sided module is presented in the Figure 2.

![Figure 2. Open-sided module (Image courtesy of Kingspan Off Site and Modular UK)](image)

The infill wall is on separated plane from the main frame, but the wall is connected to the frame. Therefore, the stability of the module can be given through cross bracing in the wall plane. This module is often found on the buildings higher than 3 stories. The wall can be formed from lighter cold-formed steel sections whenever it does not contribute to the gravity load carrying system and stability system.

4. Applicability of Modular Building Construction in Hong Kong
According to [15], Hong Kong has been implementing prefabricated building technology since the middle of 90’s. The project was Headquarter and Member Facilities of the Hong Kong Jockey Club. In the project, secondary beams and slab of 3-storey podium structure were constructed using precast element. The application of prefabricated elements in construction project in Hong Kong has been continuously extended until recent projects. Most of them use precast facades and prefab balconies to speed up the construction time. However, the application of modular volumetric
building technology has not been widely implemented. The modular building construction in Hong Kong is also called as Modular Integrated Construction (MiC) [8].

MiC is seen to be the future of construction industry in Hong Kong [16]. It is because Hong Kong is one of the most densely populated cities in the world. A housing shortage is one classical problem in this city. Therefore, Hong Kong authority for housing is pursuing prefabrication construction system to provide more public housings. It has been admitted if the prefabrication in construction is significantly increasing construction productivity.

There are some investments required to build the manufacturing facilities. Since the current modular building in Hong Kong were developed based on import product. Some other investments on the automation and robotic technology are paramount to support the prefabrication process. Nevertheless, the penetration of technology and innovation in Hong Kong construction industry will enhance the capability in providing modular building.

From the structural design view, a comprehensive design standard for this construction type must be developed. This is to protect the engineers in order to provide safe design. So far, the design practice still adopts the conventional design standard which stand independently. Stability systems and connection detailing are the key on the overall performance where these two have not been considered interactively. The advancement on construction materials are ready to support this construction to bring a more efficient and optimum structural design.

5. Benefits and Challenges Using Cold Formed

Although it uses as a secondary component, cold-formed steel member has been contributed to MiC projects. Four-sided module and continuously supported module use cold-formed steel for curtain wall element. It acts as primary structural component since the wall carry the gravity loads. In comparison, the open-sided module and corner supported module treat cold-formed steel members only for architectural supporting elements. The module relies on the hot-rolled steel profile at the corner positions or sometimes also at intermediate positions. The columns are predominantly from hollow steel section.

### Table 1. Benefit and challenges of hot-rolled and cold-formed steel structure (a)

| Comparison item | Hot-rolled steel | Cold-formed steel |
|-----------------|------------------|-------------------|
| Cross Section   | - Local buckling is unlikely to happen | - Sections are relatively easy to experience local |
| Global Stability| - Due to relatively bulky section, the member imperfection will be small so that global stability can be maintained | - Plate imperfections will affect global stability |
|                 | - Lateral torsional buckling tends to control the member design | - Members are likely to experience torsional or flexural-torsional instability |
| Residual stress | - Relatively lower | - It increases because of cold-forming process |
| Wind Load       | - It will create relatively thick steel sections because the steel strength is relatively lower | - Since the yield strength is higher, it will create relatively slender structure and it will reduce the amount of steel used |
| Seismic Load    | - It has good performance because of high ductility | - The performance is questionable because there is inadequate research in this field |
| Fire Engineering| - Strength degradation is gradually taken place on the temperature above 200oC [17, 18] | - The performance dips sharply when it exposes on temperature above 100oC [19] |
Table 1. Benefit and challenges of hot-rolled and cold-formed steel structure (b)

| Comparison item | Hot-rolled steel | Cold-formed steel |
|-----------------|------------------|-------------------|
| Durability      | - Surface preparation and coating are required to protect from corrosion | - There is no requirement for coating because it can have corrosion resistance from galvanizing process |
| Fabrication Process | - Difficult to customize the cross sections. Market availability will govern the sections used | - Relatively easy to customize the section and it takes shorter time to fabricate the built-up sections |
| Steel Structure Weight | - Since the applicability of high strength steel is limited, the normal strength steel will give bigger | - Lighter structure weight is possibly gained because the sections will be smaller due to relatively high yield |

Due to recent technology advancement, it is possible to form and roll thicker sections from cold-formed steel. It may be foreseen in the future the cold-formed steel is another option for main steel frame. Some benefits and challenges of selecting cold-formed steel in structural point of view have been summarized in Table 1.

[1] explains that the steel wall can be formed by C channels ranging from 70 to 100 mm deep. The channels are positioned in every 600 mm. The same sections are also used for ceilings and floors but with closer distance (within 400 mm). The vertical and horizontal bracing can use cold-formed or hot-rolled steel depending on the design. All those cold-formed steels are possibly made from light gauge steel. In the past, it was not easy to form thicker sections [20]. Therefore, cold-formed has not been exploited for the open frame structure.

As an example, it is presented the simple calculation of member size for corner column of 4-sided module. The column will be designed using hot-rolled steel and cold-formed steel to compare the results. It aims to use the optimum dimension. The building data consist of:
- Module size = 3.6 m x 7 m; Height = 3 m; Ultimate floor load 8 kN/m²
- Number of stories = 10, so the total force on the column in the ground floor = 10 x 8 x 2524 = 504 kN (assume there are only 4 columns on the module)
- Hot-rolled steel specification: Fy = 460 MPa
- Cold-formed steel specification: Stainless Steel Lean Duplex (EN 1.4162) F0.2 = 460 MPa
- All the sections are using Square Hollow Section (SHS)

5.1. Hot rolled-steel design
Trial section: SHS 100x100x10 (Effective Length, Le = 3m)
According to the table B.2 [21]:
Bf = Bw = 100 mm; ri = 10 mm; t = 6.3 mm; A = 2320 mm²; rx = ry = 38 mm
I = 336*10^4 mm⁴; S = 67.1*10³ mm³; Z = 80.9*10³ mm³
Since it uses S355:
\[ \varepsilon = \left( \frac{275}{F_y} \right)^{0.5} = \left( \frac{275}{460} \right)^{0.5} = 0.77 \]
Member Classification: \[ b \frac{L_f}{t_f} < 40 \varepsilon \rightarrow 100 < \frac{40}{10} \cdot 0.77 \rightarrow 10 \leq 30.93 \] (semi-compact, class 3)

Slenderness ratio \( \lambda = \frac{L_e}{r_y} = 78.95 \) Assume K = 1
using and \( F_y \) then read table 24 in (BS5950, 2000) to get \( p_c \)
Compressive strength: \( p_c = 266.25 \text{ N/mm}^2 \)
Axial compressive capacity: \( P_a = A \cdot p_c = 617.7 \text{ kN} \rightarrow \text{unity check} = 504/617.7 = 0.82 < 1 \text{(SAFE!)} \)
5.2. Cold-formed steel design

Trial section: SHS 100x100x6 (STALA, n.d.)

\( B_f = B_w = 100 \text{ mm}; \quad r_i = 10 \text{ mm}; \quad t = 6 \text{ mm}; \quad t_i = 5.96 \text{ mm} \) (BMT)

Sectional properties of unreduced sections:

\[
\begin{align*}
    b_w &= B_w - 2(t + r_i) = 100 - 2(6+10) = 68 \text{ mm} \\
    b_{cw} &= B_w - t = 100 - 6 = 94 \text{ mm} \\
    b_f &= B_f - 2(t + r_i) = 100 - 2(6+10) = 68 \text{ mm} \\
    b_{cf} &= B_f - t = 100 - 6 = 94 \text{ mm} \\
    r_c &= r_i + 0.5t = 10 + 0.5 \times 6 = 13 \text{ mm} \\
    u &= 0.5\pi r_c = 20.42 \text{ mm} \\
    c_o &= (2/\pi) r_c = 8.26 \text{ mm} \\
    A &= t_i (2b_w + 2b_f + 4u) = 6 \times (2 \times 68 + 2 \times 94 + 4 \times 20.42) = 2107.93 \text{ mm}^2 \\
    E &= 205000 \text{ MPa} \\
\end{align*}
\]

Local buckling:

Using effective widths concepts (BS5950, 1998), the properties of reduced section are as follow:

K factor: \( h = b_{cf} / b_{cw} = 1 \rightarrow \text{use curve 2: } K_1 = 7 - \frac{2h}{0.11 + h} - 1.2h^3 \approx 4 \)

\( K_1 \)

\( \rho_{cr} = 0.904 E K_1 (t_i / b_w)^2 \approx 5695 \text{ MPa} \)

\( f_c / \rho_{cr} = 460 / 5695 = 0.08 < 0.123 \)

Effective width: \( b_{eff} = b_w (\text{fully effective}) \)

Effective area: \( A_{eff} = A_g = 2107.93 \text{ mm}^2 (\text{Note: No unstiffened element on SHS section}) \)

Axial capacity due to local buckling: \( P_n = A_g f_c = 969 \text{ kN} \)

Flexural buckling:

Since from local buckling check the full section is effective, then the other section properties are calculated:

\[
\begin{align*}
    I_{corner} &= 0.149 r_c^3 t_1 = 1951.02 \text{ mm}^4 \\
    I_x &= I_y = 2 \left( \frac{b_f t_f^3}{12} + 2b_f t_1[0.5 b_{cw}]^2 + 2 t_1 b_w t_1 + 4I_{corner} + 4. \mu. t_1 (0.5 b_w + C_o)^2 \right) \\
    I &= I_x = 2399.37 + 1790527 + 312335.79 + 7804.1 + 869403 = 2.982 \times 10^6 \text{ mm}^4 \\
    \text{Mid-contour length: } p &= 2(b_w + b_f) + 4u = 353.68 \text{ mm} \\
    \text{Enclosed Area: } A_p &= b_{cw} b_{cf} - r_c^2 (4 - \pi) = 8690.03 \text{ mm}^2 \\
    Torsional Constant: J &= 4A_p t_f^2 / p = 5.09 \times 10^6 \text{ mm}^4; \text{ warping constant} = 0 \\
    G &= E / [2(1 + \nu)] = 7.885 \times 10^4 \text{ MPa} \\
    r_x &= \sqrt{(I_x/A)} = 37.6 \text{ mm} \rightarrow r_y = r_x \text{ and } x_o \\
    &= 0 \quad r_o = \sqrt{\left(r_y^2 + r_o^2 + x^2\right)} = 53.2 \text{ mm} \\
    \beta &= 1 - (x/r_o)^2 = 1 \\
    \text{Check maximum allowable slenderness: } \frac{L_E}{r_y} = \frac{3000}{37.6} = 79.79 < 180 (\text{Ok}) \\
    \text{Elastic buckling stress under minor axis: } P_{EY} &= \frac{\pi^2 E t_f}{l_E^2} = 670.38 \text{ KN} \\
    \text{Perry coefficient: } \eta &= 0.002 \left( \frac{L_E}{r_y} - 20 \right) = 0.118 \\
    \text{Short strut capacity: } P_s &= A_{eff} F_{0.2} = 825KN \rightarrow \phi = \frac{1}{2} (P_s + (1 + \eta) P_E) = 787.24 \text{ kN} \\
    \text{Flexural buckling resistance: } P_c &= \frac{P_E y_p}{(1 + \eta) y_p} = 529KN
\end{align*}
\]
Torsional buckling:

Elastic flexural buckling resistance about major axis: \( P_{EX} = \frac{\pi^2 E I_x}{L e^2} = 670.38 \text{ KN} \)

Torsional buckling load: \( P_T = \frac{g_1842}{\varphi_1842}(G ./ J + 2 \frac{\pi^2 E C_w}{L e^2}) = 141.81 \times 10^3 \text{ KN} \)

Torsional buckling load: \( P_{TF} = \frac{\varphi_1842}{2}\left[(P_{EX} + P_T) - \sqrt{(P_{EX} + P_T)^2 - 4 \cdot \beta \cdot P_{EXT} \cdot P}\right] = 670.38 \text{ KN} \)

Since \( P_{T} < P_r \), \( \alpha = 1 \rightarrow \eta = 0.002 \) (\( \alpha L_e / f_y = 20 \)) \( 0.118 \rightarrow \eta = 787.24 \text{ kN} \)

Torsional flexural buckling resistance: \( P_c = \frac{P_{TFPcs}}{\phi + \sqrt{\phi^2 + P_{TFPcs}}} = 529 \text{ KN} \)

The capacity of cold-formed steel column = min (local buckling; flexural buckling; torsional buckling)

\( P_c = 529 \text{ kN} \rightarrow \text{unity check against} \ P_a = 504/529 = 0.95 < 1 \) \( \text{(SAFE!)} \)

Both design calculations give similar results. Using almost identical sections and same yield strength have given slightly different unity check value. Proposed section of SHS 100x100x6.3 (Hot-rolled) and 100x100x6 (cold-formed) can be used to carry the loads. However, the design process of cold-formed takes more effort. Finally, it can be concluded that the cold-formed section is applicable for main structural member of modular building.

6. Summary and Conclusion

The background theory including the development of current modular building structure have been presented. Due to technology advancement, MiC projects may promote manufacturing technique in construction. There are some benefits in term of time, cost, and sustainability can be gained with modular building.

In terms of structural design, further studies are necessary especially for the feasibility in high-rise buildings. The use of cold-formed steel for main structural member also remains valid for further investigations. Cold-formed steel has been used for wall-supporting structure but the application for open frame system remains scarce. However, the example calculation shows a greater possibility of using cold-formed steel for main column structure. The calculation is to provide quick check on the feasibility of using cold-formed steel structure.

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