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Experimental and numerical investigation on the lateral force resistance of modular steel sub-frames with laminated double beam

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ABSTRACT

Modular construction was widely applied since higher integrity, faster speed and less emission. Especially for COVID-19, several modular steel hospitals were urgently built for treatment and successfully contributed to epidemic control. It has been known that laminated double beam has the capability of significantly strengthening the cooperation between adjacent floor and ceiling beams in modular steel buildings. However, the effect of the superposition of laminated double beam on the lateral force resistance of modular steel structure has not been fully understood. In present study, a series of full-scale lateral experimental tests and finite element analysis were conducted to comprehensively investigate the lateral response of modular steel sub-frames with laminated double beam. Moreover, a simple validated analytical procedure was developed to support the design and assessment of modular steel buildings in engineering practice. The results show that the application of corner plug-in junction could significantly strengthen the connection of critical components of a modular steel sub-frame. The superimposed bending action of the laminated beam was demonstrated by that the strain neutral axes of the layered beams are relatively close to the interface of the beams resulting from interfacial bolt connections. It shows that the superposition of adjacent double beams could obviously reinforce the structural integrity and lateral force resistance of a modular steel sub-frame. Furthermore, the developed analytical procedure provides an accurate and efficient method for estimating the initial lateral stiffness of modular steel sub-frames.

1. Introduction

Corner-supported modular steel buildings (CMSBs) are assembled on-site by groups of room-sized modules, completed off-site with the structures, pipelines and decoration [1], as shown in Fig. 1(a). CMSBs have demonstrated the advantages of high prefabrication rate, rapid construction speed and friendly environment impact [2,3], which are highly instrumental in the development of construction industrialization [4,5]. Especially during the outbreak of COVID-19, the Huoshenshan hospital in Wuhan was built in only 10

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days adopting the modular construction technology as shown in Fig. 1(b), which significantly contributed to the successful control of the COVID-19 pandemic outbreak [6]. This convincingly illustrates the social significance of modular steel buildings.

In CMSB systems, the modules are typically connected by corner bolted or welding joints [7]. Due to the requirement for connecting working space, the gaps between floor and ceiling beams occur resulting in the formation of corner segment columns and double beams [8], which can affect the lateral performance of a CMSB system [9–11]. Anan et al. [12,13] performed a comparative lateral tests on the modular and regular steel-braced frames, which indicated an obvious variation in the force distribution pattern. Fathieh et al. [10, 14–16] conducted the static and dynamic analysis of multi-storey CMSB systems. An independent bending deformation of double beams was observed and the intensive inelasticity of corner segment columns occurred under lateral load, which could cause the failure of the MSB system. Considering the combined action of adjacent components, Sharafi et al. [17,18] investigated the overall mechanical property of interlocking modular buildings. Their results indicated that the combination of adjacent columns and beams significantly improved the robustness of MSBs. The above-mentioned studies showed that the lateral performance is unsatisfied for the CMSB systems with only corner junctions [19], especially for the high-rise modular steel buildings, and the cooperative interaction of the adjacent components highly strengthened the overall mechanical capacity [20]. As the existing studies mostly focused on the mechanical performance of entire structural systems, it was necessary to further understand the bearing mechanism of modular steel sub-frames under lateral load.

It has been known that the intermediate connections could highly affect the structural integrity, in particular the details of modular junctions (e.g., with or without gap between adjacent beam components). Chen at el [21–23] studied the mechanical performance of the beam-to-beam bolted connection and cover plate welded connection. The results showed that the independent double beams were unable to mechanically work together; consequently the plastic deformation occurred at the ends of ceiling beams, which could significantly reduce the ductility of modular junctions. Deng et al. [24] presented the self-lock corner connection, which could be conveniently assembled on-site without the restrictions of working space, while the double beams still could not function synergistically as a composite beam. Ma and Xia et al. [25] designed a novel plug-in connection which could avoid the interlayered gaps and realize the overlap of double beam structures. Their results showed that this inter-module connection could result in a superior structural integrity and mechanical performance, and therefore was applied in the modular steel sub-frames in this study.

The cooperation of the adjacent floor and ceiling beams was comprehensively investigated in previous studies. The study on the strength of back-to-back double channel beams demonstrated that the web connections could enhance the flexural performance of double beams [26]. In addition, a theoretical study of Zha et al. [27] on the bending behaviours of laminated beams in CMSBs showed that the double beam structure exhibited an obvious composite effect resulting from the interfacial connectors. Xu et al. [28,29] proposed the laminated channel beams with interfacial friction and bolt connections in CMSBs, and systematically investigated their flexural behaviours. It was found that the neutral axes of the upper and lower layers transferred to the interfaces illustrating the superimposition of the laminated double beams. Owing to the interfacial constraints, the laminated double beams had the capability of cooperatively sharing external load. Although much previous research works have been conducted to understand the mechanical behaviour of double beams in CMSBs, the effect of the superimposition of laminated double beams on the lateral performance of CMSBs has not been fully understood so far. Therefore, it becomes necessary to further investigate the lateral performance of modular steel buildings with laminated double beam.

The purpose of this study is to investigate the lateral performance of modular steel sub-frames with laminated double beam as shown in Fig. 2 by conducting a series of experimental, numerical and theoretical studies. Fig. 3 shows the research route with methodology, content and process. The lateral failure modes, load-displacement curves, ultimate capacities, initial stiffness and strain distribution characteristics of the modular steel sub-frames were analyzed. In addition, the interlayered tangential forces and the lateral resisting mechanism of the modular steel sub-frames with laminated beam were discussed. On this basis, a simplified analytical procedure was developed to estimate the initial lateral stiffness of the proposed modular steel sub-frames.
2. Experimental program

2.1. Description of modular steel sub-frame specimens

To investigate the mechanical performance of CMSBs with laminated double beam, the lateral tests on the four full-scale planner modular steel sub-frame specimens were conducted. In accordance with the GB 50017-2017 standard [30] and design handbook for modular structures [31], a nine-storey modular steel frame were designed with the typical 3D modular room sizes of $6 \times 3 \times 3.1$ (m$^3$).

As shown in Fig. 2, the four-planner modular steel sub-frame specimens taken from the bottom two-storey of the modular group were comprised of the upper half module, the lower half module and the interlayer connections. Fig. 4 indicates the geometrical details of the modular steel sub-frame specimens. The upper and lower column members were taken to the inflection point with a length of 1550
(mm), and the cold-formed square tubes were designed as the columns with a cross-section of $200 \times 200 \times 12$ (mm). The novel plug-in modular joint developed in previous study [25] was applied in vertical corner connection for overcoming the difficulties in on-site assembly and avoiding the inter-layer gap as shown in Fig. 5. First, the single beam and column components in modular units were individually welded in factory and the bolt holes were opened for corner connection. Then, the modular steel frames were connected by the pre-manufactured plug-in device and split bolts without the requirement for on-site welding process and interlayer operation space. Thus, the modular group can be conveniently installed, while the double beams can be easily overlapped.

In conventional CMSBs, the floor and ceiling beams independently undertook 3.5:1 proportional loads, and the modular frames behaved individually subjected to lateral load [10, 24]. The innovative corner connections in proposed modular steel frames could eliminate the gaps between floor and ceiling beams, and thereby the mutual constraints was enhanced between double beams for cooperatively sharing the loading as illustrated in Fig. 6. In particular, the laminated channel beams with different interfacial connections were designed in specimens, labelled as MSF-LFCB-C, MSF-LFFB-C, MSF-LFCB-4B, MSF-LFFB-4B, respectively. As for

![Fig. 4. Geometrical details of the specimens of a modular steel sub-frame.](image)

![Fig. 5. Assembly details of the corner joints.](image)
specimen MSF-LFCB-C, the simply laminated double beam, with only interface contact interaction, was comprised of the two channels with the cross-sections of 300 × 150 × 6 (mm) and 200 × 150 × 6 (mm). For standardization in production, the same dimensions were adopted for floor and ceiling beams. Therefore, the simply laminated beam with two equal channels of section 300 × 150 × 6 (mm) was fabricated in specimen MSF-LFFB-C. In comparison, two strongly laminated channel beams connected by the interfacial bolts at 1050 (mm) intervals were designed for specimens MSF-LFCB-4B and MSF-LFFB-4B to enhance the interfacial constraints of adjacent double beams. Similarly, the channel beam sizes of specimens MSF-LFCB-4B and MSF-LFFB-4B were consistent with specimens MSF-LFCB-C and MSF-LFFB-C, respectively. Due to the limitation of test device, the spans of beams were all selected as 4200 (mm) in this study. The dimensions of components of sub-frame specimens were summarized in Table 1.

All specimens were made of Q235B steel. Prior to the experiments, the coupon tensile tests were performed to determine the material properties of the specimens. According to the GB/T 2975-2018 standard [32], three groups of standard coupons were derived from the same batch of tubular column, inner sleeve and channel beam components, respectively. The uniaxial tensile tests were performed on the three repeating coupon specimens in each group using the universal testing machine in accordance with the GB/T 228.1–2010 standard [33]. Arranging strain gauges and load cells, the stress-strain curves of all samples were obtained and the material mechanical parameters were determined. The averaged results are shown in Table 2. In addition, the material properties of the split bolt and the high strength bolt were provided by manufacturer, as listed in Table 2. Moreover, the friction coefficient of contact surface in specimens was tested to be 0.21.

### 2.2. Lateral test setup and instrumentation

The experiments were conducted in the State Key Laboratory for Geomechanics and Deep Underground Engineering at China University of Mining and Technology. The lateral test setup was arranged as shown in Fig. 7. The planner modular steel sub-frame specimens were laid up parallel to the ground considering the operability and safety of lateral loading. Five pairs of channel restraining clamps were placed at the middle positions of columns and laminated beams to prevent the out-of-plane deformation. The lower column bases were connected to two pedestals by the hinged support, and the pedestals were fixed to the concrete ground with anchor bolts to strictly restrain the translation. The reaction beam was amounted to the ground with anchor bolts and the pulling jack with a 3000 kN capacity was placed at the right side to provide lateral load. Besides, a load cell was installed at the top of the pulling jack to record the loading value. The jack was connected to the force transmitting girder by a rigid steel pole. The upper column tops were hinged with the force transmitting girder, and thereby the lateral load was applied to the sub-frame specimens. In addition, two pairs of channel restraint apparatuses were arranged at the girder to ensure the in-plane lateral loading. It should be mentioned that, as this paper mainly focused on the lateral force resistance of modular steel sub-frames, and it was difficult to provide constant vertical axial loads on the specimens for this test setup, the influence of vertical forces on the overall lateral performance was ignored in present study.

Due to the large size of the full-scale modular steel sub-frames, a Dajiang unmanned aerial vehicle (UAV) was set to monitor the overall deformation of these specimens in top view. The digital image correlation (DIC) optical measuring technique was applied in the

### Table 1

| Specimens  | Column $b_i \times b_i \times t_i$ | Floor beam $h_i \times w \times t_i$ | Inner sleeve $b_i \times b_i \times t_i$ | Ceiling beam $h_i \times w \times t_i$ | $l_i$ | $l_o$ | $l_i$ | $l_o$ |
|------------|----------------------------------|------------------------------------|---------------------------------------|-------------------------------------|-----|-----|-----|-----|
| MSF-LFCB-C | 200 × 200 × 12                   | 300 × 150 × 6                      | 176 × 176 × 10                        | 200 × 150 × 6                       | 1550 | 4200 | 500 | –   |
| MSF-LFFB-C | 200 × 200 × 12                   | 300 × 150 × 6                      | 176 × 176 × 10                        | 300 × 150 × 6                       | 1550 | 4200 | 600 | –   |
| MSF-LFCB-4B| 200 × 200 × 12                   | 300 × 150 × 6                      | 176 × 176 × 10                        | 200 × 150 × 6                       | 1550 | 4200 | 500 | 1050|
| MSF-LFFB-4B| 200 × 200 × 12                   | 300 × 150 × 6                      | 176 × 176 × 10                        | 300 × 150 × 6                       | 1550 | 4200 | 600 | 1050|

Fig. 6. Bearing diagram of double beams.
experiments to obtain the strain distribution regulation at left corner region based on speckle image correlation principle. The DIC optical instrument with two industrial cameras was installed, as shown in Fig. 7. For DIC analysis, random speckle with diameter of 2 mm–3 mm were sprayed on the observed panel zone in advance. Specially, the calibration was conducted to determine the ratio of speckle pixels and actual distance prior to lateral test. During the lateral test, the DIC optical device worked synchronously with loading in blue light environment and the speckle images of observed area were captured at a frequency of 10 Hz. Then, these numerous images were post-processed using GOM software and the strain field of the left joint area can be produced in this way.

Fig. 8 indicates the instrumentation scheme for the lateral tests. It can be seen that four linear variable displacement transducers

| Components      | $E$ (GPa) | $f_y$ (MPa) | $\varepsilon_y$ | $f_u$ (MPa) | $\varepsilon_u$ |
|-----------------|-----------|-------------|-----------------|-------------|-----------------|
| Column          | 196       | 315         | 0.02            | 423         | 0.13            |
| Inner sleeve    | 200       | 328         | 0.02            | 419         | 0.14            |
| Beam            | 194       | 320         | 0.00134         | 410         | 0.14            |
| Split bolt      | 206       | 980         | 0.05            | 1030        | 0.12            |
| High strength bolt | 206    | 980         | 0.05            | 1030        | 0.12            |

Note: (1) $E$ is the elastic modulus; (2) $f_y$ is the yielding strength; (3) $\varepsilon_y$ is the yielding strain; (4) $f_u$ is the ultimate strength; (5) $\varepsilon_u$ is the strain value at ultimate state.

Fig. 7. Details of experimental set-up.

Fig. 8. Layout of the measurement devices. (a) LVDT and DIC arrangement; (b) Strain gauges assignment.
(LVDTs), numbered as L1−4, were installed at the left side columns to measure the lateral displacement of the specimens. Specifically, the displacement of column top was recorded by L1, while L4 was used to monitor whether the pedestal occurred the rigid body movement. In addition, L2 and 3 were placed at corner joint area. Similarly, four LVDTs, numbered as L5−8, were installed at the right-side columns to sufficiently obtain the lateral displacement results. Four LVDTs, labelled as L9−12, were placed at the bottom flange of ceiling beam to measure the vertical displacement of laminated beam at the corner region. The positions of LVDTs were marked in Fig. 8(a). In addition, a series of strain gauges were installed on the column flanges and beam end sections at corners to specifically measure the strains of column and beam components under lateral load. As shown in Fig. 8(b), eight strain gauges, numbered as RC-1–4 and LC-1–4, were installed on the inner and outer flanges of the column sections at left and right corners. Ten strain gauges were attached to the flange and web of beam end sections.

The modular sub-frame specimens were firstly loaded to the 10% of their estimated capacities for examining the workability of test equipment. Then, the formal lateral tests were performed with the increase of 10 kN each step. The tests stopped when the lateral load decreased below 85% of ultimate bearing capacity of specimens or when lateral deformation was excessively large for safety concerns.

3. Experimental results

3.1. Lateral deformation behaviour and failure modes

Due to the test device limitation, the effect of column axial forces on the lateral performance of modular steel sub-frames was disregarded in this study. The overall deformations of modular steel sub-frames with laminated double beams were surveyed using the UAV. Moreover, the local deformations were observed during loading and the failure modes of the specimens were recorded as shown in Fig. 9. For specimen MSF-LFCB-C, the lateral bending deformation of columns and the antisymmetric bending deformation of laminated beam was detected. When the load was increased to 120 kN, the local buckling was observed on the compression flanges of beam end sections. As the load reached to 140 kN, the interfacial slip of laminated beam was noted and the local buckling became more obvious. While the slip and gap of column-to-column junctions were still unnoticeable indicating the superior connecting strength of the novel plug-in joint. As the loading continued, the rapid decrease in horizontal load occurred indicating the reduction in bearing capacity of specimen MSF-LFCB-C. The applied lateral loading stopped when the lateral load reduced to 120 kN and the deformed state at the end of test was shown in Fig. 9(a). A similar deformation pattern and failure mode was observed for specimen MSF-LFFB-C. With the height of ceiling beam increased, the local buckling of beam flanges occurred when the lateral load reached to 150 kN. At a load magnitude of 170 kN, the interfacial slippage of the laminated double beam was observed, especially at the mid-span section. Once

![Fig. 9. Lateral deformation and failure modes. (a) MSF-LFCB-C; (b) MSF-LFFB-C; (c) MSF-LFCB-4B; (d) MSF-LFFB-4B.](image-url)
overall lateral deformation was over certain limit which could cause safety issues, the test stopped, and the failure deformation of specimen MSF-LFFB-C was recorded as shown in Fig. 9(b).

Four bolt connections were installed at the interface of laminated double beam to enhance the structural integrity of specimens MSF-LFCB-4B and MSF-LFFB-4B. For the MSF-LFCB-4B, the local buckling of beam ends was observed when the load reached to 140 kN. The interfacial slip and bolt shearing behaviours were detected at the ultimate lateral capacity of 160 kN, while the reduction in bearing capacity deterioration was also observed. The test was terminated when the lateral load decreased to 135 kN as shown in Fig. 9(c). Specimens MSF-LFFB-4B exhibited the similar deformation behaviour under lateral load applied on upper column top. The interfacial slippage behaviour occurred at the load of 180 kN. After that, the lateral displacement significantly increased with the increase of loading. Finally, the lateral test was terminated when the lateral displacement of column top reached to 122 mm, as shown in Fig. 9(d).

In general, the lateral bending deformations of columns and the antisymmetric bending deformations of double beams occurred in all specimens under lateral load. The innovative corner junction demonstrated a great integration performance by preventing the column-to-column slippage. The antisymmetric flexural properties of laminated beams could significantly affect the lateral performance of modular steel sub-frames. As for MSF-LFCB-C and MSF-LFFB-C, only contact interaction was seen between the double beams. Comparatively, adding the bolt connections at the interfaces of laminated beams in MSF-LFCB-4B and MSF-LFFB-4B could highly promote the collaboration between the adjacent beams, and thereby enhancing the structural integrity of modular steel sub-frames. Therefore, MSF-LFCB-4B demonstrates a better performance in local deformation than MSF-LFCB-C, while the lateral resistance of MSF-LFFB-4B is better than MSF-LFFB-C.

3.2. Lateral capacity and initial stiffness

The lateral forces were constantly monitored by the load transducer during the loading process. The remarkably low lateral displacements of pedestals measured by L4 and L8 (close to zero) demonstrated the perfect translation constraints of column bases. Moreover, the lateral displacements of upper column tops were recorded by L1 and 5. The lateral load-displacement curves were shown in Fig. 10. The results showed that the lateral force-displacement curves were almost linear at the initial stage of loading. For the specimens with different sized layered beams, the load-displacement curves can be classified into three major stages: elastic stage, yielding development stage, and bearing degradation stage. In the yielding development stage, the local buckling of the end sections of the beams was observed, resulting in the structural nonlinearity of sub-frame specimens. When the obvious local deformation and interfacial slippage occurred, the specimens reached to their ultimate capacities. The sub-frames then tended to failure due to the serious local buckling of ceiling beams. The bearing failure of specimens for the layered beams with the same size can be divided to two stages, i.e., elastic stage and yielding development stage. After the yielding load point, the similar nonlinear lateral deformations of these two specimens were gradually developed, which led to the distinct decease of scant stiffness of corresponding load-displacement curves.

Specifically, the lateral properties of modular steel sub-frames were summarized in Table 3. The MSF-LFFB-C exhibited the 25% and 21% higher yielding and ultimate load values than the MSF-LFCB-C, respectively. The yielding and ultimate capacities of the MSF-LFFB-4B were higher 29% and 18% than the MSF-LFCB-4B, individually. Moreover, the initial lateral stiffness, defined by the ratio of load to displacement in initial stage, is discussed in this study. The MSF-LFFB-C and MSF-LFFB-4B presented 68% and 88% greater initial lateral stiffness than that of MSF-LFCB-C and MSF-LFCB-4B, respectively. It was noted that the increase of ceiling beam size could directly enhance the section modulus of laminated double beams and the restraint ratio of ceiling beam to lower column. Hence,

![Fig. 10. Lateral load-displacement curves.](image-url)
the lateral capacity and stiffness of the MSF-LFFB-C and MSF-LFFB-4B could be highly improved. On the other hand, the yielding load, ultimate lateral capacity and initial stiffness of specimen MSF-LFCB-4B were 17%, 14% and 58% higher than that of specimen MSF-LFCB-C, respectively. These lateral mechanical functions of specimen MSF-LFFB-4B were 20%, 15% and 76% higher than specimen MSF-LFFB-C, respectively. This indicates that the interfacial bolts could strengthen the superimposed bending property of laminated beams. Therefore, the modular steel sub-frames with strongly laminated double beams could produce a better overall resistance performance compared to the modular sub-frames with simply laminated double beams.

3.3. Mechanical response of novel corner joint

The mechanical performance of the innovative plug-in junction used in the modular steel sub-frames was analyzed. Using the horizontal load measured by force transducer, the bending moment of corner joints can be calculated. The horizontal inclination angle of columns was monitored by L2 and 3, and the vertical slope angle of beam end was measured by L9 and 10. Hence, the relative rotation of connection region can be obtained. On this basis, the moment-rotation curves of the left corner joints in modular sub-frame specimens can be determined, as depicted in Fig. 11(a). This shows that the trend of moment-rotation curves of joints is consistent with that of the load-displacement curves. The yielding moment of the junction in specimen MSF-LFCB-C was 186 kN m with the corresponding rotation of 0.0004. In addition, the yielding moment of joint in specimen MSF-LFFB-C was up to 233 kN m at the corresponding rotation of 0.00039. Comparatively, the yielding capacities of the MSF-LFCB-4B and MSF-LFFB-4B were increased to 217 kN m and 279 kN m with the corresponding rotations of 0.00046 and 0.00043, respectively. In summary, the plug-in junctions showed the great initial rotation stiffness and satisfied load capacity. According to node classification from EN 1993-1-8: 2005 Eurocode3 [34] as illustrated in Fig. 11(b), the corner connection applied in these specimens can be identified as rigid joint. This provides the basis for the following analytical model establishment of modular steel sub-frames.

3.4. Strain distribution in the ends of the laminated beams

The strain developments of joints and components were obtained by DIC technique and gauges. Fig. 12 shows the Mises strain distribution of joint panel regions in the failure stage, and the strain values of column flanges at corners were presented in Fig. 13. It was indicated that the plastic strains mainly concentrated in the ends of beams while the columns are still in elastic state for all specimens. As the control section of the specimens, the strain distribution of laminated beam ends was evaluated. Owing to the antisymmetric deformation of double beams under lateral load, more intention was paid to the left end sections of double beams. Fig. 14 shows the strain development at different distance from the interface as the load gradually increased until the ultimate state was reached. As shown in Fig. 14(a), the strain at the ends of laminated beam in MSF-LFCB-C remained at a relatively low level during the initial stage. The strain values then gradually increased with the relatively higher strain of ceiling beam than that of floor beam, and the rate of strain increased with the increase of the lateral load. Moreover, the strains of the layered beam sections were linearly distributed and the strain axes of the upper and lower beams were still consistent with the layered centroid axes. At the ultimate capacity of 140 kN, the plastic strain was observed on the flange of ceiling beam. For the MSF-LFFB-C, the similar strain distribution in the ends of laminated beam was seen as shown in Fig. 14(b), while disparity of upper and lower beams were improved with the same

### Table 3

Lateral performance of modular steel sub-frame specimens.

| Specimens         | F_y (kN) | F_u (kN) | K_i (kN/m) | H_fy (%) | H_fu (%) | H_k (%) |
|-------------------|----------|----------|------------|----------|----------|----------|
| MSF-LFCB-C        | 120      | 140      | 3.3 × 10^3 | –        | –        | –        |
| MSF-LFFB-C        | 150      | 170      | 5.6 × 10^3 | 25%      | 21%      | 68%      |
| MSF-LFCB-C-4B     | 140      | 160      | 5.3 × 10^3 | 17%      | 14%      | 58%      |
| MSF-LFFB-C-4B     | 180      | 195      | 9.9 × 10^3 | 50%      | 43%      | 196%     |

Note: (1) F_y is the lateral yielding capacity; (2) F_u is the lateral ultimate capacity; (3) K_i is the initial lateral stiffness; (4) H_fy is the improvement of the yielding capacity; (5) H_fu is the improvement of the ultimate capacity; (6) H_k is the improvement of the initial stiffness.

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![Fig. 11.](image-url) Fig. 11. Moment-rotation responses of corner joints. (a) Moment-rotation curves of corner joints; (b) Connection classification from Eurocode3.
size of layered beams. It was found that the strain neutral axes of the floor and ceiling beam ends all coincide with their centroid axes for the MSF-LFCB-C and MSF-LFCB-C, indicating that the dependent bending deformations occur on the simply laminated double beams.

As shown in Fig. 14(c), the strains in the end of laminated beam in specimen MSF-LFCB-4B were linearly distributed on the cross section of floor and ceiling beams. With the interfacial bolt connections, the strain neutral axes of the layered beams individually
deviated by 50 mm and 25 mm from their centroid axes to the interface. The laminated double beam in specimen MSF-LFFB-4B presents the similar sectional strain development as shown in Fig. 14(d). As the height of ceiling beam added to be equal to floor beam, the deviation of the strain neutral axes was 50 mm. Compared with the simply laminated double beams, the interfacial shearing connections highly enhanced the cooperation between the adjacent floor and ceiling beams, resulting in the deviation of strain neutral axes from the centroid axes to the interfaces. This indicated that the superimposed bending behaviour of laminated beams was produced and the strongly connected double beam structures showed the mechanical characteristics of the integral beam to a certain extent. Therefore, the strengthened laminated beams exhibited the superior structural integrity and the corresponding modular steel

Fig. 14. Strain distribution in the end sections of laminated beams. (a) MSF-LFCB-C; (b) MSF-LFFB-C; (c) MSF-LFCB-4B; (d) MSF-LFFB-4B.

Fig. 15. FE model of specimen MSF-LFCB-4B with mesh, boundary condition and load mode.
sub-frames showed the greater lateral performance than the sub-frames with simply laminated beam.

4. FE simulations and lateral resisting mechanism analysis

4.1. FE model development and validation

Finite element analysis (FEA) was performed using the commercial software ABAQUS to further understand the interlayered forces and the lateral resisting mechanism of modular steel sub-frames with laminated double beam. 3D FE models of the modular steel sub-frame specimens were developed using 8-noded C3D8R solid elements for avoiding shear self-locking and hourglass in FEA. As an example, Fig. 15 illustrates the FE model of specimen MSF-LFCB-4B with mesh, boundary condition and load mode. The mesh convergence analysis was conducted to determine the appropriate mesh sizes and capture the mesh independent solutions for FE simulations. The geometrical dimensions of specimens were set to the same as the experiments, and the prefabricated wielding connections in module were defined as tie method since the welding action was regarded as the rigid response. The boundary conditions and load mode were selected to be consistent with the experimental tests. The trilinear stress-strain model was used to describe the steel mechanical property of FE models and the material parameters were assigned according to the coupon test results as listed in Table 2. The contact action between the components was simulated by the “surface to surface” algorithm in ABAQUS software. Specifically, the normal behaviour was selected as the “hard” contact type and the tangential behaviour was defined as the penalty method with the tested friction coefficient. In addition, the nlgeom was set in lateral loading steps to include the nonlinear effects of large deformations.

A comparison of the numerical and experimental results was conducted. Fig. 16 indicates that the lateral deformations of the FE models agree well with test observations in terms of beam end local buckling, interfacial bolt shearing and failure modes. Moreover, the lateral load-displacement curves reconstructed in ABAQUS are compared with the experimental data as presented in Fig. 17. It can be seen that the numerical curves are in excellent agreement with the test results. Furthermore, the lateral mechanical properties of yielding capacity, yielding displacement and initial lateral stiffness were quantitatively compared as listed in Table 4. It can be found from the comparisons that the differences between the FEA predications and experimental data all keep less than 6%. This further validates the dependability of the FE models. Consequently, it is reliable to evaluate the interlayer forces, and understand the lateral bearing mechanism of modular steel sub-frames based on the verified FE models.

4.2. Modeling interlayer forces between upper and lower modules

The interlayered shearing forces were obtained from the validated 3D FE models of modular steel sub-frames as shown in Fig. 18. Without the vertical load applied, the interaction between the adjacent double beams in specimens MSF-LFCB-C and MSF-LFFB-C was
Fig. 17. Comparison of lateral load-displacement curve from FE simulation with experimental results.

Table 4
Comparison of numerical prediction of lateral mechanical properties with experimental results.

| Specimens          | $F_{\text{exp}}$ (kN) | $F_{\text{num}}$ (kN) | $D_{\text{exp}}$ (mm) | $D_{\text{num}}$ (mm) | $K_{\text{exp}}$ (kN/m) | $K_{\text{num}}$ (kN/m) | $E_f$  | $E_d$  | $E_k$  |
|--------------------|------------------------|------------------------|------------------------|------------------------|--------------------------|--------------------------|--------|--------|--------|
| MSF-LFCB-C         | 120                    | 121                    | 46.11                  | 43.71                  | $2.60 \times 10^3$      | $2.75 \times 10^3$      | 1%     | −5%    | 6%     |
| MSF-LFFB-C         | 150                    | 155                    | 42.98                  | 43.92                  | $3.49 \times 10^3$      | $3.52 \times 10^3$      | 3%     | 2%     | 1%     |
| MSF-LFCB-4B        | 140                    | 146                    | 46.57                  | 47.58                  | $3.01 \times 10^3$      | $3.07 \times 10^3$      | 4%     | 2%     | 2%     |
| MSF-LFFB-4B        | 180                    | 186                    | 45.89                  | 47.13                  | $3.92 \times 10^3$      | $3.94 \times 10^3$      | −3%    | −3%    | −1%    |

Note: (1) $F_{\text{exp}}$ is the experimental yielding force; (2) $F_{\text{num}}$ is the numerical yielding force; (3) $D_{\text{exp}}$ is the experimental yielding displacement; (4) $D_{\text{num}}$ is the numerical yielding displacement; (5) $K_{\text{exp}}$ is the experimental initial lateral stiffness; (6) $K_{\text{num}}$ is the numerical initial lateral stiffness; (7) $E_f$ is the error between numerical and experimental yielding force; (8) $E_d$ is error between numerical and experimental yielding displacement; (9) $E_k$ is the error between numerical and experimental initial lateral stiffness.

Fig. 18. Interlayered tangential forces. (a) MSF-LFCB-C; (b) MSF-LFFB-C; (c) MSF-LFCB-4B; (d) MSF-LFFB-4B.
basically unnoticeable, and therefore the independent bending deformation of the laminated beams occurred under the lateral load. Hence, the interfacial tangential forces of the laminated double beams were merely inconspicuous and the lateral load was mainly transferred through the plug-in devices as presented in Fig. 18 (a) and (b). As the symmetrical structures, the shearing forces at the left and right corners were basically consistent value of 80 kN at the yielding state. As for specimens MSF-LFCB-4B and MSF-LFFB-4B, the upper and lower modular frames were extra bound by the interfacial bolts, which provided the shear stiffness for the laminated beams. As a result, the horizontal load was synthetically delivered by the corner junctions and the interfacial shearing connections. The interlayered tangential forces were engendered including the column-to-column shearing forces and the bolt shearing forces at interfaces of laminated beams as shown in Fig. 18(c) and (d). The corner shearing forces were obviously reduced compared with the MSF-LFCB-C and MSF-LFFB-C, which indicates that the shearing forces in corner joints could be alleviated owing to the interfacial mechanical connections. Moreover, the distributions of interfacial shearing forces principally tallied with parabola model, consistent with the relative slippage feature of the laminated double beams.

4.3. Modeling lateral resisting mechanism

The lateral resisting mechanism of the modular steel sub-frame with laminated double beams was further analyzed. For specimen MSF-LFCB-C and MSF-LFFB-C, as the lateral loads were mainly undertaken by the inter-module joints, the mutual constraints of modular sub-frame groups were primarily provided by the corner junctions. Comparatively, the four bolts were added at the interfaces of laminated double beams in specimens MSF-LFCB-4B and MSF-LFFB-4B, which significantly enhanced the combined action between the floor and ceiling beams. Thus, the horizontal load transfer path was enriched and the interactive constraint between the upper and lower modules was reinforced. The superimposition of laminated double beams highly influenced the lateral performance of modular steel sub-frames. For the simply laminated beams in the MSF-LFCB-C and MSF-LFFB-C, the floor and ceiling beams independently bent under lateral load. Relatively, the interfacial mechanical connections enhanced the cooperativity of the double beams in the MSF-LFCB-4B and MSF-LFFB-4B. Thus, the strongly laminated beams exhibited the superimposition effect illustrated by the deviations of stress neutral axes to interface. Consequently, the effective bending stiffness of the bolt-laminated double beams was enhanced, and the beam-column stiffness ratio was reinforced, which could promote the initial lateral stiffness and bearing capacity of modular steel frames. As a result, the specimens with bolt-laminated beams exhibited the superior structural integrity and lateral performance compared with the specimens with only corner connections.

5. Analytical analysis of the initial lateral stiffness of modular steel sub-frames

Under small deformation of the modular structures, the additional displacement and internal forces caused by axial load had little influence in the lateral stiffness so that the initial lateral stiffness of the modular steel sub-frames with laminated double beam could be estimated by ignoring the second order effect. Firstly, a series of assumptions were adopted as follows: (1) the axial forces in beam components were ignored; (2) all components of modular steel sub-frames behaved elastically; (3) the beam-to-column connections in each module were assumed as the rigid nodes. In addition, the inter-module plug-in connections exhibited the excellent stiffness in lateral experiments, so that the connections could be treated as the rigid joints in accordance with EN 1993-1-8: 2005 Eurocode3 [34]. Hence, the corner junctions were assumed to be rigid in the derivation. Based on the boundary conditions and load mode in the lateral tests, the simplified mechanical model of modular steel sub-frames is established as shown in Fig. 19(a), where P denotes the total lateral load, \( l_c \) is the length of upper and column, \( l_0 \) indicates the span of laminated beam, and \( l_e \) describes the linear stiffness of column. In particular, the laminated double beam is simplified to the integral beam component considering the superimposed bending effect, and \( l_{eb} \) represents the equivalent linear stiffness of laminated beam. Furthermore, \( l_c \) and \( l_{eb} \) can be obtained as follows: \( l_c = E_l c / l_c \), \( l_c = E_l c / l_{eb} \), where \( E, l_c \) and \( l_{eb} \) are the elastic modulus, the section inertia moment of column and the equivalent section inertia moment of laminated beam, respectively. Owing to the symmetry of modular steel sub-frame specimens and the uniformity of boundary conditions, the mechanical model of semi-structure is further developed as shown Fig. 19(b) , where \( l_{eb} \) denotes the equivalent linear stiffness of the laminated beam.

![Fig. 19. Mechanical model of modular sub-frame. (a) Overall model; (b) Half model.](image-url)
stiffness of half span laminated beam.

Then, the relationship of the lateral load and the displacement for the half mechanical model was further analyzed. As for the half mechanical model, both the mid-span section of beam and the lower column base were restrained by hinged support, and the lateral load was applied to the upper column top. Thus, the lateral displacement of modular structure is produced as indicated in Fig. 20(a), where \( \Delta \) denotes the lateral displacement of column top. Correspondingly, the supporting reaction forces are presented in Fig. 20(b). On this basis, the section moment of column and beam components caused by external lateral force and standard lateral forces are presented in Fig. 20(c) and (d), individually. Finally, the lateral displacement of column top can be calculated using the diagram multiplication method [35] as Equation (1).

\[
\Delta = \sum_{i=1}^{3} \int_{0}^{l_i} \frac{M_{p}M_i}{EI_i} \, dx
\]  

(1)

where \( i, l_i, M_i, M_{p}, \) and \( I_i \) represent the component number, the component length, standard section moment of component, section moment of component caused by the lateral load and the section inertia moment of component, respectively. Furthermore, the relationship between lateral load and displacement can be described using Equation (2). The initial lateral stiffness \( (K) \), defined by the ratio of lateral load to displacement at the elastic stage, is obtained by Equation (3). Based on Equations (2) and (3), the initial lateral stiffness can be further derived as shown in Equation (4).

\[
\Delta = \frac{P l_c^2}{3} \left( \frac{l_c}{E I_c} + \frac{l_0}{E I_{eb}} \right)
\]  

(2)

\[
K = \frac{P}{\Delta}
\]  

(3)

\[
K = \frac{3}{l_c^2 \left( \frac{1}{E I_c} + \frac{1}{E I_{eb}} \right)}
\]  

(4)

It is noted that the effective bending stiffness calculation of the laminated beams plays an important role in the initial lateral stiffness derivation of the modular steel sub-frames. Xu et al. [28,29] systematically conducted a series of investigations on the

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**Fig. 20.** Mechanical analysis model. (a) Restraints and displacement; (b) Supporting reaction forces; (c) Section moment force caused by lateral load; (d) Section moment force caused by standard lateral load.
superimposed bending behaviours of the laminated channel beams, and proposed the effective bending stiffness estimation formulas of the double beam structures with different interfacial connections. Specifically, the equivalent bending stiffness of the simply laminated beam and the strong laminated beam with four bolt connections were predicted by Equations (5)–(8) [28, 29], respectively.

\[
\begin{align*}
E_{LFCB-C} &= EI_{lb} + EI_{lb} \\
E_{LFFB-C} &= 2EI_{lb} \\
E_{LFCB-4b} &= EI_{lb} + EI_{lb} + \frac{1}{36}EA_{b}h_{b}^{2} + \frac{1}{16}EA_{b}h_{b}^{2} \\
E_{LFFB-4b} &= 2EI_{lb} + \frac{1}{18}EA_{b}h_{b}^{2}
\end{align*}
\]

Equations (5)–(8), the initial lateral stiffness of modular steel sub-frames with laminated double beam can be calculated using Equations 9–12, individually.

\[
\begin{align*}
K &= \frac{3}{EI_{lb} + \frac{h_{lb}}{EI_{lb} + EI_{hb}}} \\
K &= \frac{3}{EI_{lb} + \frac{h_{lb}}{EI_{lb} + EI_{hb}} + \frac{h_{hb}}{EI_{lb} + EI_{hb}} + \frac{h_{cb}}{EI_{lb} + EI_{cb}}} \\
K &= \frac{3}{EI_{lb} + \frac{h_{lb}}{EI_{lb} + EI_{hb} + EI_{hb} + EI_{cb}}}
\end{align*}
\]

The estimation of initial lateral stiffnesses by Equations 9–12 are compared with the experimental and numerical results in present study as shown in Table 5. The comparison results indicate that the estimated initial lateral stiffnesses agree well with the experimental data and the FE simulated results with the maximum error within 10% for all specimens. In addition, it is observed that the analytical predictions of initial lateral stiffness are slightly higher than experimental and numerical results, and this may be due to the constraining imperfections occurred in lateral tests as well as FE simulations and the ideal assumption of boundary conditions in mechanical models for modular steel sub-frames. Moreover, the statistical analysis is performed to evaluate the discreteness of the experimental, numerical and calculated results as presented in Table 5. It shows that the standard deviation coefficients keep less than 4%, which indicates the considerably small data difference. It should be mentioned that the comparative analytical methods and codes are not applicable for the proposed modular steel sub-frames due to the distinctiveness of joint detail and laminated beam structures. Generally, the calculation equations of the initial lateral stiffness are highly validated and the analytical procedure in this study exhibits the superior reliability.

6. Conclusions

In this study, the laminated double beam was introduced into the CMSBs to enhance the mutual constraints between upper and lower modules. The lateral performance of the modular steel sub-frames with laminated double beam was systematically investigated

| Specimens | \( K_{exp} \) (kN/m) | \( K_{num} \) (kN/m) | \( K_{cal} \) (kN/m) | \( E_{cal-exp} \) | \( E_{cal-num} \) | \( \bar{E} \) (kN/m) | \( \sigma \) (kN/m) | \( V_{e} \) |
|-----------|----------------------|----------------------|----------------------|----------------|----------------|----------------|----------------|-------|
| MSF-LFCB-C | 2.60 \times 10^3 | 2.75 \times 10^3 | 2.85 \times 10^3 | 10% | 4% | 2.73 \times 10^3 | 103 | 4% |
| MSF-LFFB-C | 3.49 \times 10^3 | 3.51 \times 10^3 | 3.52 \times 10^3 | 1% | 0% | 3.51 \times 10^3 | 14 | 0% |
| MSF-LFCB-4B | 3.01 \times 10^3 | 3.07 \times 10^3 | 3.25 \times 10^3 | 8% | 6% | 3.11 \times 10^3 | 102 | 3% |
| MSF-LFFB-4B | 3.92 \times 10^3 | 3.94 \times 10^3 | 3.92 \times 10^3 | 0% | -1% | 3.93 \times 10^3 | 10 | 0% |

Note: (1) \( K_{exp} \) is the experimental initial lateral stiffness; (2) \( K_{num} \) is the numerical initial lateral stiffness; (3) \( K_{cal} \) is the calculated initial lateral stiffness; (4) \( E_{cal-exp} \) is the error between the calculated and experimental initial lateral stiffness; (5) \( E_{cal-num} \) is the error between the calculated and numerical initial lateral stiffness; (6) \( \bar{E} \) is the average value of the experimental, numerical and calculated results; (7) \( \sigma \) is the standard deviation of the experimental, numerical and calculated results; (8) \( V_{e} \) is the standard deviation coefficient of the initial stiffness results, and \( V_{e} = \sigma / \bar{E} \).
by conducting a series of the mechanical tests in conjunction with FE simulations. In addition, a simplified analytical procedure was developed to estimate the initial lateral stiffness of the modular steel sub-frames. The following are the major conclusions:

- The local buckling failure happened in the ends of laminated beams under lateral load. The corner plug-in junction could enhance the joining strength, and thereby effectively minimize the column-to-column discontinuity in CMSBs. The design of the modular steel sub-frames follows the principle of strong column and weak beam.
- The superimposed bending behaviour of the laminated beam could highly influence the lateral stiffness and capacity of a modular steel sub-frame. Compared to a modular steel sub-frame with simply laminated beam, the application of the strongly laminated double beam could increase the yielding capacity, ultimate capacity and initial lateral stiffness of the modular sub-frame by around 25%, 20% and 70%, respectively.
- Owing to the interfacial bolt connections, the strain neutral axes of floor and ceiling beams approached to the interface, which indicating the cooperative bending response of laminated double beam. In addition, the interfacial mechanical connectors can effectively support the interlayered shearing force.
- The superimposition of adjacent double beams could reinforce the mutual constraint between the upper and lower modules, enhance the effective stiffness of laminated beam, and ultimately significantly promote the structural integrity and lateral performance of a modular steel sub-frame.
- The developed analytical procedure with consideration of the effective stiffness of laminated double beam could provide an accurate estimation of the initial lateral stiffness of modular steel sub-frames.

Declaration of competing interest

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.

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