Simulations of corrugated steel bracing reinforcing infilled RC frame: influence factors

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Abstract. Based on the experimental infilled reinforced concrete (RC) frames strengthening by corrugated steel bracing, finite element (FE) analysis is carried out to compare with experimental research. Hysteresis curves, envelope curves, stiffness curves and failure modes of the corrugated steel bracing are studied to reveal the structural performance. Corrugated steel bracing is designed to resist lateral load in reinforcing concrete buildings. The results show that the deviations of the yield loads between test results and simulation are 11.1 % (forward direction) and 9.17 % (backward direction); the maximum loads between test results and simulation are 9.09 % (forward direction) and 6.52 % (backward direction), respectively. Ten models are studied to considering the key factors of corrugated steel bracing. The results show that the stiffness and maximum loads (forward and backward) are improved as the thickness increases. The ductility is reduced as the thickness increases.

1. Introduction
Steel bracing had been used extensively as the lateral force-resistant components in strengthening reinforced concrete (RC) frames structures. In recent years, some studies[1-4] had been conducted experiments and finite element modeling in strengthening RC buildings with steel bracing and some of which would be mentioned in the followings. Hadad[5] tested four frames under cyclic loading. One was bare, the second was reinforced by concrete bracing, the third was strengthened with steel bracing and the fourth was infilled with solid cement bricks. The results showed that the improving strength was different with different types of reinforcement methods. The energy dissipation of the braced and infilled frames was always higher than that of bare frame. Tahamouliroudsari[6] investigated different types of braces to strengthen RC frames. There were eight frames in the test and one of them was bare. Seven frames were retrofitted with different braces such as the X-brace, the knee brace, the chevron brace, the eccentric brace and the chevron brace with a vertical link. The results indicated that the eccentric brace has a better performance compared to the other specimens. X-brace showed excellent stiffness and strength than that of other steel bracing reinforcement methods. Kai Qian[7] compared the load-resisting function of the braced frames to the bare frame. It indicated that steel braces improved the behavior of RC frame and mitigated progressive collapse effective.

According to the above results, steel bracing can improve the strength and stiffness of RC frames greatly. On the basis of these researches, corrugated steel bracing was studied as a new type of steel bracing in reinforcing RC frames. Cao and Feng[8] had conducted experimental study. Test results
showed that the strength, stiffness, energy dissipation of strengthened specimen has been improved greatly. However, there is little finite element study on corrugated steel bracing in reinforcing RC frames with infill walls at present.

The objectives of this research are to study the establishment of finite element models. Concrete and corrugated steel are two different materials. It is difficultly to simulate them work together. The details of simulation can be seen in the paper. The main factors, which affect the seismic performance of the structure, are researched as well.

2. Infilled RC frame with corrugated steel bracing tests and materials

2.1. Infilled RC frame with corrugated steel bracing tests
The test prepared two specimens, which were called Specimen 1 (S1) and Specimen 2 (S2). S1 and S2 had the same dimensions. The story height was 1.2 m and clear span was 1.8 m. The reduced scale was 1/3. S2 was reinforced by corrugated steel bracing with infill walls and S1 was bare without infill walls and corrugated steel bracing. At the end of the second story, there was an electro-hydrostatic actuator to provide low cycled reversed loading. On the top of two columns, hydraulic jacks provided support reaction. There were displacement meter on the right side of the specimen. Force and displacement data were collected by computer. The two specimens can be seen in Cao and Feng[8].

2.2. Materials
The average compressive strength of concrete cubes was 30.78 MPa as per ACI 318-05[9]. The yield strength of longitudinal bars and transversal ties were 382.11 MPa and 390.36 MPa, respectively. The average compressive strength of fired common brick was 53.61 MPa as per ACI 530-02 / ASCE 5-02 /TMS 402-02[10]. The yield strength of corrugated steel was 264.15 MPa and the thickness was 0.4 mm.

3. Finite element model

3.1. Constitutive models
The stress-strain curves of concrete, steel bar and corrugated steel can be seen in Feng[11]. The shape and characteristics of the concrete curve reflected the mechanical properties of the concrete materials. Concrete model was based on second degree parabola as per code for design of concrete structures (GB50010, 2010)[12]. The decline of the curve was a skew line, which recommended by Hognestad[13]. The stress-strain curves of steel bar and corrugated steel was an ideal elastoplastic model was simplified two straight lines.

3.2. The simplified model of infill walls
The test indicated that the main cracks of infill walls develop along the diagonal line. The cracks were called as shear fracture. This experimental phenomenon can be seen as a diagonal brace, which bore pression but not tension. The equivalent diagonal brace model was proposed by Polyakov[14].

3.3. Comparison with test results

3.3.1 Failure modes of corrugated steel bracing
Failure modes of corrugated steel bracing on the first and second floor are shown in Figure 1 (a) (in test), Figure 1 (b) (in simulation), Figure 1 (c) (in test) and Figure 1 (d) (in simulation). On the first floor, wave trough had the largest stress in simulation, especially the central region. Failure modes of the test were also had the largest deformation in the middle of corrugated steel bracing. On the second floor, there was a smaller deformation and stress at the end of corrugated steel bracing. The comparison results indicated that corrugated steel bracing improved the bearing capacity of the specimen and played a positive role.
Figure 1. Failure modes of profiled steel sheet bracing.

3.3.2 Comparative study of hysteresis curves
Comparisons of hysteretic curves (Specimen S1 and Specimen S2) are shown in Figure 2 (a) and Figure 2 (b). Test results and finite element results are presented in Table 1 and Table 2.

Table 1. Loads and displacements (S1)

| Load direction | $P_y$ (kN) | $\Delta_y$ (mm) | $P_{max}$ (kN) | $\Delta_{max}$ (mm) |
|----------------|------------|----------------|---------------|---------------------|
| Test           |            |                |               |                     |
| forward        | 32.74      | 19.8           | 37.14         | 67.2                |
| backward       | 30.13      | 18.75          | 40.14         | 68.5                |
| Simulation     |            |                |               |                     |
| backward       | 31.29      | 20.77          | 42.26         | 75                  |

$P_y$: Yield load; $\Delta_y$: Yield displacement; $P_{max}$: Maximum load; $\Delta_{max}$: Displacement at maximum load
Table 2. Loads and displacements (S2)

| Load direction | \( P_y \) (kN) | \( \Delta y \) (mm) | \( P_{\max} \) (kN) | \( \Delta_{\max} \) (mm) |
|----------------|----------------|-----------------|----------------|----------------|
| Test           |                |                 |                |                |
| forward        | 99.77          | 25.73           | 142.2          | 103.69         |
| backward       | 90.64          | 20.43           | 122.46         | 51.87          |
| Simulation     |                |                 |                |                |
| forward        | 89.81          | 25.95           | 130.35         | 103.8          |
| backward       | 83.03          | 23.86           | 130.45         | 103.8          |

\( P_y \): Yield load; \( \Delta y \): Yield displacement; \( P_{\max} \): Maximum load; \( \Delta_{\max} \): Displacement at maximum load

It can be seen from the figures that yield loads of Specimen 1 (S1) in forward and backward direction were 32.74 kN and 30.13 kN in the test, respectively. During the same period, the yield loads in modeling were 33.06 kN and 31.29 kN in forward and backward direction. The deviations of the results were 0.98 % and 3.85 %, respectively. The maximum loads of forward and backward direction were 37.14 kN and 40.14 kN in the test. The maximum loads were 40.83 kN and 42.26 kN in finite element. The deviations of maximum loads were 9.94 % and 5.28 %, respectively.

The deviations of Specimen 2 (S2) were 11.1 % and 9.17 %, respectively. The maximum loads of forward and backward direction were 142.2 kN and 122.46 kN in the test. The maximum loads were 130.35 kN and 130.45 kN in finite element. The deviations of maximum loads were 9.09 % and 6.52 %, respectively.

3.3.3 Comparative study of envelope curves

The comparisons of envelope curves between test and simulation are shown in Figure 3. Yield loads and the maximum loads of the test and finite element model are presented in Table 1 and Table 2.

It can be seen from the figures that the lines almost coincided in initial elastic phase. When the specimen came into the elastic-plastic phase, envelope curves were on the rise and bearing capacity enhanced. Corrugated steel bracing undertook the lateral loads under cyclic loading. Test results were higher than that of simulation in the figures. One reason was that the load point was on the second beam end in the FE model; the specimens were restrained by the long steel bar along the beam length in the test. Another reason was that infill walls could undertake some tension strength, but the simplified model supported the pressure only.

3.3.4 Comparative study of stiffness

The comparison of stiffness curves between test and simulation are shown in Figure 4. It can be seen from the figures that the secant stiffness of S1 were 5.36 kN/mm and 5.0 kN/mm in test and simulation. The ultimate stiffness of S1 were 0.59 kN/mm and 0.55 kN/mm. The deviations of secant stiffness and ultimate stiffness were 6.72 % and 6.78 %, respectively.

It can be seen from the figures that the secant stiffness of S2 were 11.19 kN/mm and 12.10 kN/mm in test and simulation. The ultimate stiffness of S2 were 1.17 kN/mm and 1.26 kN/mm. The deviations of secant stiffness and ultimate stiffness were 8.13 % and 7.69 %, respectively.
4. Influence factors
On the basis of these studies, it was necessary to extend the range of examples of FE models. Feng[15] analysed the influence of thickness and types on structural bearing capacity. Therefore, the influences of thickness and types on stiffness, ductility and maximum loads (forward and backward) are discussed in this paper. The main influence factors were listed as follows: thickness and types of corrugated steel bracing. Thickness was selected such as 0.4mm, 0.6mm, 0.8mm, 1.0mm, 1.2mm. Types of corrugated steel bracing were YX21-180-900 and YX35-187.5-750 (Ⅰ). The thickness and types of corrugated steel bracing are presented in Table 3.

Table 3. The thickness and types of corrugated steel bracing

| Thickness (mm) | YX21-180-900 | YX35-187.5-750 (Ⅰ) |
|----------------|--------------|------------------|
| 0.4mm          | 12.63        | 12.73            |
| 0.6mm          | 13.65        | 14.33            |
| 0.8mm          | 14.31        | 15.82            |
| 1.0mm          | 15.11        | 17.22            |
| 1.2mm          | 16.01        | 19.71            |

4.1. Stiffness

4.1.1 Thickness study
The stiffness of YX21-180-900 and YX35-187.5-750 (Ⅰ) are shown in Figure 5 (a) and Figure 5 (b). The stiffness at different thicknesses is presented in Table 4. It can be seen from the figures, the thicker corrugated steel bracing had higher secant stiffness. The stiffness decreased gradually as the displacement increased. When the displacement was within 30 mm, the stiffness sharp declined. The initial cracks of RC frame contributed the rapid decline in stiffness. With the increase of displacement, the stiffness was declined stably. The ultimate stiffness was also had the same pattern. The thicker corrugated steel bracing, the greater stiffness.

(a) The stiffness of YX21-180-900  (b) The stiffness of YX35-187.5-750 (Ⅰ)
Figure 5. The stiffness of YX21-180-900 and YX35-187.5-750 (Ⅰ)

Table 4. The stiffness at different thicknesses and types.

| Thickness (mm) | YX21-180-900 | Ultimate stiffness (kN/mm) |
|----------------|--------------|-----------------------------|
| 0.4            | 12.63        | 1.15                        |
| 0.6            | 13.65        | 1.25                        |
| 0.8            | 14.31        | 1.47                        |
| 1.0            | 15.11        | 1.37                        |
| 1.2            | 16.01        | 1.49                        |

| Thickness (mm) | YX35-187.5-750 (Ⅰ) | Ultimate stiffness (kN/mm) |
|----------------|---------------------|-----------------------------|
| 0.4            | 12.73               | 1.10                        |
| 0.6            | 14.33               | 1.15                        |
| 0.8            | 15.82               | 1.25                        |
| 1.0            | 17.22               | 1.36                        |
| 1.2            | 19.71               | 1.37                        |
4.1.2 Types of corrugated steel bracing study
The stiffness of YX21-180-900 and YX35-187.5-750 (I) are shown in Figure 5 (a) and Figure 5 (b). The stiffness at different types is presented in Table 4. The results showed that larger wave height (YX35-187.5-750 (I)) gained higher stiffness. The secant stiffness of structure was improved greatly.

4.2. Ductility

4.2.1 Thickness study
The ductility of YX21-180-900 and YX35-187.5-750 (I) are shown in Figure 6. The yield displacement, maximum displacement and ductility of YX21-180-900 and YX35-187.5-750 (I) are presented in Table 5. The maximum displacements were unified value for better comparison. It can be seen from the figures that there were small fluctuations as the increase of thickness of corrugated steel bracing. The value of ductility was above 4.0. It indicated that corrugated steel bracing contributed to the ductility of infilled RC frame. The ductility was declined as the increase of thickness.

Table 5. Ductility of YX21-180-900 and YX35-187.5-750 (I)

| Thickness (mm) | $\Delta_y$ (mm) | $\Delta_u$ (mm) | $\mu = \frac{\Delta_u}{\Delta_y}$ |
|----------------|-----------------|-----------------|---------------------------------|
| YX21-180-900   |                 |                 |                                 |
| 0.4            | 26.09           | 129.75          | 4.97                            |
| 0.6            | 26.27           | 129.75          | 4.94                            |
| 0.8            | 28.99           | 129.75          | 4.48                            |
| 1.0            | 29.12           | 129.75          | 4.48                            |
| 1.2            | 30.04           | 129.75          | 4.32                            |
| YX35-187.5-750 (I) |       |                 |                                 |
| 0.4            | 27.95           | 129.75          | 4.64                            |
| 0.6            | 28.27           | 129.75          | 4.59                            |
| 0.8            | 29.99           | 129.75          | 4.33                            |
| 1.0            | 30.12           | 129.75          | 4.31                            |
| 1.2            | 31.04           | 129.75          | 4.18                            |

$\Delta_y$: Yield displacement; $\Delta_u$: Maximum displacement; $\mu$: Ductility.

4.2.2 Types of corrugated steel bracing study
The ductility of YX21-180-900 and YX35-187.5-750 (I) are shown in Figure 6. The yield displacement, maximum displacement and ductility of YX21-180-900 and YX35-187.5-750 (I) are presented in Table 5. The results indicated that the two types of corrugated steel bracing were gained good ductility. The larger wave height (YX35-187.5-750 (I)) gained lower ductility.

4.3. Maximum loads (forward and backward)

4.3.1 Thickness study
The maximum loads (forward and backward) of YX21-180-900 and YX35-187.5-750 (I) are shown in Figure 7. The maximum loads (forward and backward) at different thicknesses are presented in Table 6. It can be seen from the figures that the thickness was larger; the maximum loads of forward and
backward direction were higher. The results showed that the bearing capacity improved as the thickness increased. The range of increase (YX21-180-900) was 2 % ~ 10 %. The range of increase (YX35-187.5-750 (I)) was 4 % ~ 13 %.

4.3.2 Types of corrugated steel bracing study

The maximum loads (forward and backward) of YX21-180-900 and YX35-187.5-750 (I) are shown in Figure 7. The maximum loads (forward and backward) at different thicknesses are presented in Table 6. It can be seen from the figures that the deviations of yield loads about YX21-180-900 and YX35-187.5-750 (I) were 3 %, 1 %, 4 %, 4 %, 6 %, respectively. The deviations of maximum loads about YX21-180-900 and YX35-187.5-750 (I) were 12 %, 15 %, 5 %, 11 %, 9 %, respectively. When the thickness of corrugated steel bracing was the same, the types of corrugated steel bracing with larger wave height (YX35-187.5-750 (I)) can improve the bearing capacity more obvious.

![Figure 7. The strength degradation of YX21-180-900 and YX35-187.5-750 (I)](image)

Table 6. Loads of YX21-180-900 and YX35-187.5-750 (I)

| Thickness (mm) | Load direction | \( P_y \) (kN) | \( P_{\text{max}} \) (kN) |
|---------------|----------------|----------------|------------------------|
| 0.4           | forward        | 89.13          | 149.21                 |
|               | backward       | 92.56          | 132.81                 |
|               | forward        | 90.96          | 152.0                  |
|               | backward       | 94.53          | 146.69                 |
| YX21-180-900  | 0.6            | forward        | 94.10                  | 164.46                 |
|               | backward       | 98.84          | 161.0                  |
|               | forward        | 99.20          | 173.10                 |
|               | backward       | 105.21         | 165.32                 |
|               | forward        | 106.04         | 181.04                 |
|               | backward       | 112.19         | 174.22                 |
|               | 1.0            | forward        | 91.68                  | 149.36                 |
|               | backward       | 89.58          | 148.73                 |
|               | forward        | 96.12          | 155.34                 |
|               | backward       | 93.48          | 168.49                 |
|               | 1.2            | forward        | 105.49                 | 164.88                 |
|               | backward       | 103.01         | 168.80                 |
|               | forward        | 112.12         | 172.87                 |
|               | backward       | 109.43         | 183.73                 |
|               | 1.2            | forward        | 121.20                 | 195.31                 |
|               | backward       | 119.34         | 190.42                 |

\( P_y \): Yield load; \( P_{\text{max}} \): Maximum load

5. Conclusions

RC frame and infilled RC frame strengthened with corrugated steel bracing were investigated in this paper. Finite element analysis is verified with test results. For extending the range of examples, ten
models are simulated to study the influence of key parameters. Based on the researches, the following conclusions can be drawn:

Failure modes, hysteresis curves, envelope curves and stiffness curves of Specimen 1 (S1) and Specimen 2 (S2) were studied in comparison with the experimental. The comparative results showed that finite element models were consistent with test results. The deviation of strength was 6.52 %–11.1%. Corrugated steel bracing enhanced the bearing capacity and stiffness greatly.

With the thickness of corrugated steel bracing increasing, the secant stiffness of the structure was enhanced gradually. The secant stiffness of the structure was improved by selecting larger wave height YX35-187.5-750 (Ⅰ) than that of lower wave height YX21-180-900.

With the thickness of corrugated steel bracing increasing, the ductility was declined as the increase of thickness. The ductility of the structure was improved by selecting lower wave height YX21-180-900 than that of larger wave height YX35-187.5-750 (Ⅰ).

With the thickness of corrugated steel bracing increasing, the bearing capacity of the structure was improved significantly. The bearing capacity of the structure was enhanced by selecting larger wave height YX35-187.5-750 (Ⅰ) than that of lower wave height YX21-180-900.

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