13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1112

BEHAVIOR OF STEEL FRAMES WITH AND WITHOUT AAC INFILLED WALLS SUBJECTED TO STATIC AND CYCLIC HORIZONTAL LOADS

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SUMMARY

Steel frame with infilled walls is a popular structural system used for buildings. Autoclaved Aerated Concrete（AAC）Masonries are common elements for infilled walls used in China for steel frames. The static and hysteretic behavior of steel frames with AAC infilled walls is a subject which is deserved to study for the purpose of earthquake resistance. For this, static and repeated and reversed tests of four full-scale steel frames of single-bay and two-story with and without AAC infilled walls are carried out. Based on the experiments and theoretical modelling, the static and hysteretic feature of the steel frames with AAC infilled walls subjected to static and cyclic horizontal loads is analyzed. The effects of the AAC infilled walls on the behavior of steel frames are also studied through experimental and theoretical comparison on steel frames with and without AAC infilled walls.

INTRODUCTION

Autoclaved Aerated Concrete(AAC) is a new light-weight building material used broadly in China. AAC has many advantages such as lightness, fine thermal protection behavior, excellent fire resistance, convenience for construction and environment- friendliness. Hence, AAC is used widely in all kinds of buildings.

Steel frame structures can be infilled with AAC masonry for partition. With regard to this kind of structure, the familiar design method is to let steel frames support all the vertical and horizontal loads, while the infilled walls are not treated as a part of the load-bearing structures and some measures must be taken to avoid loads being transferred on them. Apparently, this design method is inappropriate. Actually, infilled walls not only serve as the outer enclosure wall、inner partition wall and elevator wall architecturally, but also help to resist the horizontal loads structurally when steel frames subject to horizontal loads. So, the improved design method is to consider the infilled walls as lateral force resistance wall properly and consider the effect of infilled walls on steel frames.

Although many large-scale frame tests have been conducted in the past years[1~4], the majority of them are of only reinforced concrete frames infilled with brick masonry[1~3] or steel frame infilled with reinforced concrete walls[4]. In this paper, tests of four full-scale steel frames of single bay and two stories with and without AAC infilled walls are carried out in order to study the effects of infilled walls

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on load-bearing behavior of steel frames. What's more, theoretical analysis is also undertaken to compare with the experimental results.

TEST FRAMES

Four specimens of steel frames were tested. Two have AAC infilled walls and two have not. Each of the four frames could be classified as a planar, single-bay and two-story sway frame with full lateral restraint and rigid joints.

Two dimensional system

Many common steel frame structural systems can be idealized for the purposes of analysis and design as simplified two-dimensional assemblages. Ultimately three-dimensional advanced analysis of frames with and without AAC infilled walls is a desirable objective. However, it is practical and appropriate to first develop and verify a model using two-dimensional frames before attempting to include the additional complexity involved in three-dimensional analysis. The four test frames described in this paper were therefore all two dimensional, although it is anticipated that future research will involve large-scale testing of three-dimensional steel frame systems.

Dimension

The dimensions of all the test frames were identical as 4.5 m wide in the X-direction,2.35 m high from the column-base to the second story, and 2.35m high from the second story to the roof. Fig. 1 shows the dimensions of the test frames. The dimensions were carefully decided to avoid local buckling. The slendernesses (*L*c / *r*) of the column members of the first and the second story were all 48, which were representative of typical structures.

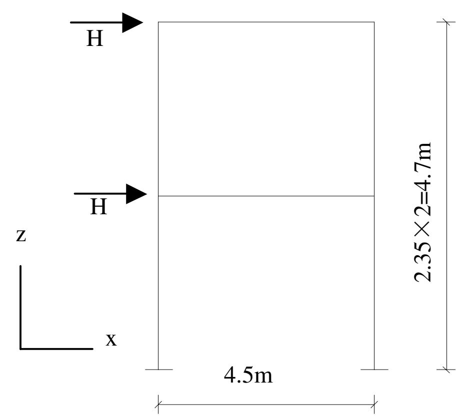


Fig.1. Dimension and loading condition of a test frame

Out-of-plane restraint

The objective of the tests and analyses was to investigate the effects of AAC infilled walls on the in-plane stiffness and strength of two-dimensional frames. In order to achieve this objective it was necessary to take some measures to preclude out-of-plane buckling of the test frame.

Structural connections

Structural connections can be classified as either rigid with infinite moment capacity, pinned with zero moment capacity, or semi-rigid with a finite moment capacity and a stiffness, which can be expressed as a function of the rotation. In this test, the object is not to research the behavior of semi-rigid connections, so all the beam to column connections were fully welded to make rigid connection. In addition, the column base plate connections were made as rigid as possible by using 40-mm thickness base plates continuously fillet-welded to the columns. Each base plate was fastened to the reinforced concrete floor girder using four M30 structural bolts with the center-to-center distance of 200 mm for each connection. Fig. 5 shows the connection of the column base.

Sections

Welded sections were used for all four frames. The dimensions and properties of the section are listed in Table 1. The section is compact so that it is not susceptible to local buckling. Failure by elastic and inelastic local buckling of a single member would not be appropriate in investigating global behavior of the test frame.

Size of AAC masonry and connection between frame and wall

The sizes of these masonries are 600×120×250mm(width×thickness×height), 300×120×250mm and 600×120×150mm. There is a L-type iron(see Fig. 7) dimensioned by 120×120×60×1mm (length1×length2×Width×thickness)with one limb welded on the web of column and the other limb nailed into the AAC masonry at intervals of 500mm(two layers of masonry). The gap between AAC wall and beam(column) is 20mm, filled by gas-forming agent after completing the construction of the wall. Before the first-story wall is constructed the 20-mm-thick 1:3 cement mortar base is painted on the reinforced concrete floor girder and the same operating method is taken for the two-story wall. Fig. 8 and Fig.9 shows the constructing phase and the completion phase of the AAC infilled walls respectively.

Material

Material used for the steel frames was grade Q235 steel with nominal yield stress of 235 MPa, commonly used in China, and material for infilled walls was grade A3.5 light AAC masonry.

TEST SET-UP AND INSTRUMENTATION

The test frames were tested in a schenck electro-hydraulic testing systems in the structural static laboratory of the TongJi University. The general arrangement of the test set-up is illustrated in Fig. 2. The lateral bracing and loading equipment are shown in Fig. 3 and the reinforced concrete floor girder is shown in Fig. 4.

Electrical resistance strain gauges were used to measure strains at each end of the beams and columns (see Fig.6). The most highly stressed region at the base of the column was monitored with particular interest in order to obtain the maximum strains. Displacement transducers were used to measure the in-plane horizontal deflections at the floor girder、at the base and two beam-column joints of right-hand column and the out-of-plane horizontal deflections at the mid-span of first-story steel beam. The relative in-plane horizontal (sway) deflection of the frame was calculated by subtracting the in-plane horizontal deflection at each story level of the right-hand beam-column joint from the in-plane horizontal deflection of the floor girder. This relative deflection and the horizontal load (H) were used to plot an in-plane horizontal load–deflection curve, suitable for comparison with the corresponding analytical results. The output from the strain gauges and displacement transducers were fed directly into the computer system, allowing the response of the frame to be closely monitored during testing.

TEST PROCEDURE

The following procedure was used to obtain accurate and reliable results for each test frame:

1) The fabricated test frame was moved into position in the test rig and the base plates were fastened to the floor girder.
2) The lateral bracing systems were set-up and kept touched closely between the strut and the beam.
3) The out-of-plumbness imperfections of the columns (in-plane and out-of-plane) were measured using plumb lines (see Fig.3)and were not considered significant for unbraced frames.
4) The load actuators were secured in position. The strain gauges and displacement transducers were placed in position. The pressure transducers, displacement transducers, and strain gauges were connected to the computer system.
5) A trial load of 20 percent of the expected ultimate capacity was applied and released in order to remove slack in the system and to ensure functionality. The frame with or without AAC infilled wall was then gradually loaded to failure(keeping the two horizontal loads the same value). The computer recorded strains and deflections for each load increment.

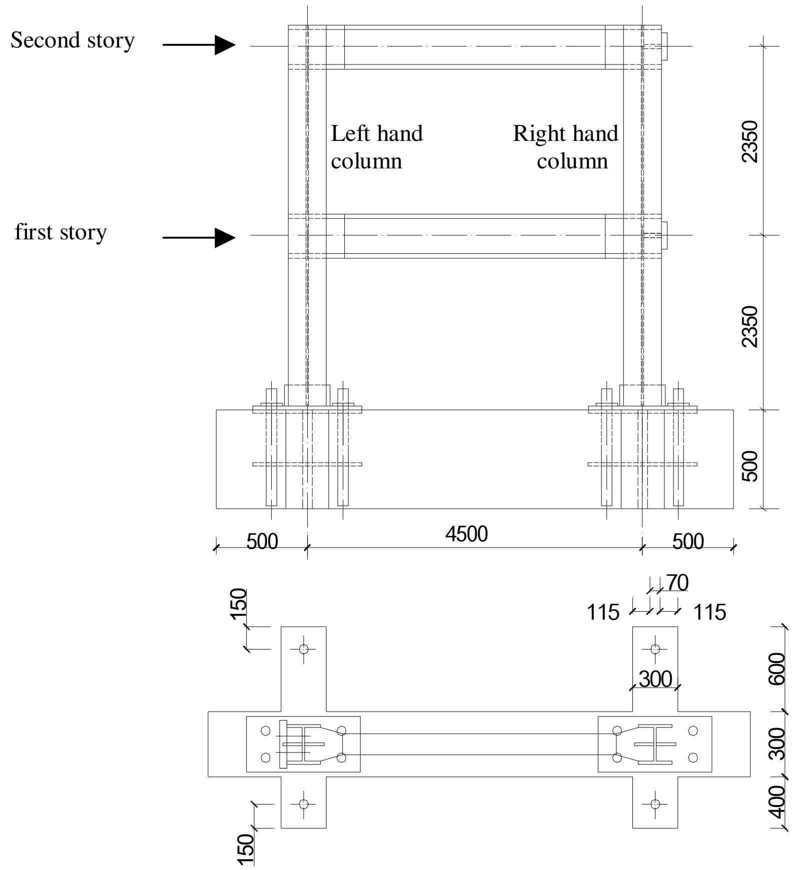


Fig.2.Elevation and top view of test frame

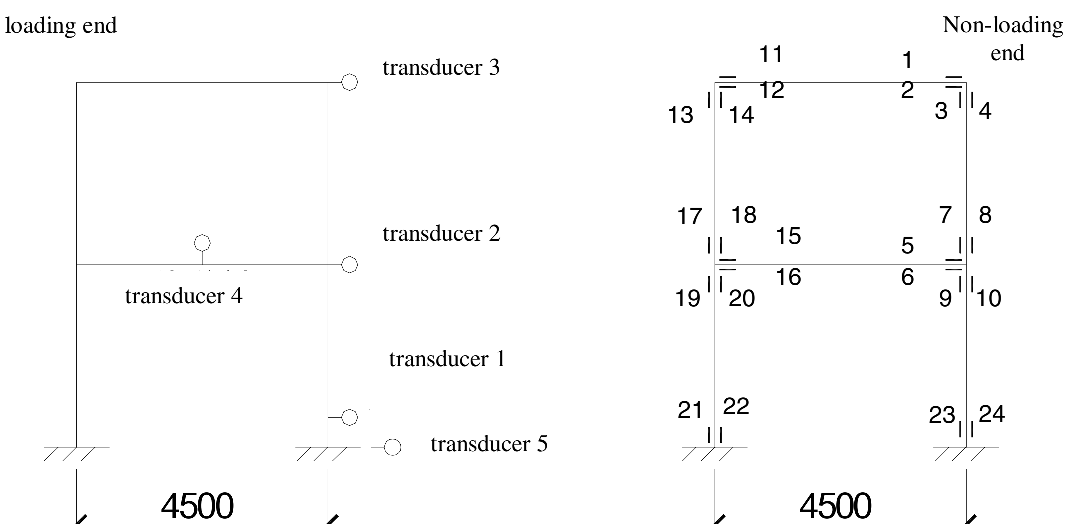
Fig.3. lateral bracing and loading equipment

Fig.4. reinforced concrete floor girder

Table 1 Sections used in the test frame

	Height H (mm)	Width B (mm)	Thickness of flange t_f (mm)	Thickness of web t_w (mm)	Axial area A_g (mm^2)	Moment of inertia about X axis $I_x(10^6mm^4)$	Moment of inertia about Y axis $I_y(10^6mm^4)$
beam	300	120	12	6	4536	70.27	3.46
column	250	200	12	8	6608	75.73	16.01

Fig.5. Horizontal jack and column base, showing strain gauges and displacement transducers



a) Displacement transducers arrangement

b) Strain gauges arrangement

Fig.6. Arrangement of displacement transducers and strain gauges

Fig.7. L-type connection between column and masonry

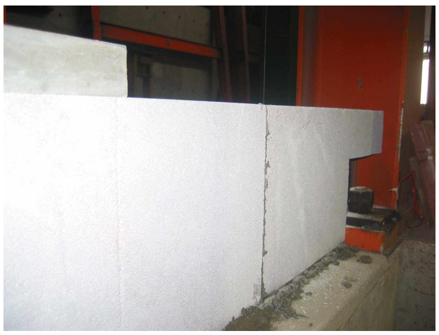


Fig.8.constructing the wall

Fig.9. the completed wall(with gas-forming agent has been filled between frame and wall)

TEST RESULTS AND NUMERICAL ANALYSIS

Material test

Mechanical properties of steel were obtained by tensile testing. The tensile testing was conducted in accordance with the Chinese standard GB228-87[5]. The measured dimensions of the beam members and the column members as listed in Table 2. Four group specimens were tested. Each group consisting three specimen was taken from the flange and web of the beam and column members, respectively(GB1、GB2 stands for flange and web of the beam；GB3、GB4 stands for flange and web of the column). The specimens had higher yield stresses ranging from 272 to 323 MPa than the nominal yield stress of 235 MPa. The ultimate stress of the specimens was approximately 450 MPa which was within the range of the nominal stress of 375–460 MPa.

Table 2 Testing results of mechanical properties of steel material

Group	Speci-men number	dimensions (mm)	fy (MPa)	fu (MPa)	E（10^5MPa）	δ (%)	Mean value of fy (MPa)	Mean value of fu (MPa)	Mean value of E (10^5MPa)	Mean value of δ (%)
1	GB1	11.70×30.10	295	470	1.90	32.5	295	452	2.03	34.3
	GB1	12.00×30.30	300	440	2.15	36.0				
	GB1	11.60×30.10	290	445	2.03	34.5				

2	GB2	6.16×30.34	320	465	2.15	37.0	322	458	2.00	36.8
	GB2	6.12×30.30	320	455	2.00	36.0				
	GB2	6.12×30.30	325	455	2.05	37.5				
3	GB3	11.80×30.18	300	450	1.95	35.5	293	445	2.03	36.2
	GB3	11.70×30.20	295	445	2.00	37.5				
	GB3	11.70×30.18	285	440	2.15	35.5				
4	GB4	7.86×30.28	270	430	2.18	41.0	273	428	2.11	39.3
	GB4	7.80×30.30	275	430	2.15	38.0				
	GB4	7.80×30.30	275	425	2.00	39.0				

Test frame 1(without AAC infilled wall, static monotonic loading)

The two horizontal loads were applied simultaneously in a ratio of approximately 1:1. The loads were initially applied in 4 increments of approximately 10 kN per horizontal actuator and a smaller load increments of approximately 5 kN per horizontal actuator. Smaller load increments were used to accurately trace the non-linear response of the frame after the onset of yielding.

At a load of 83 kN per horizontal actuator the frame began to unload indicating that the maximum capacity of the frame had been achieved. The frame failed due to a reduced stiffness caused by yielding and spread of plasticity caused by the combined effect of axial compression force and bending moment. Plastic deformations and inelastic local buckling were observed at the base of the columns as shown in Fig. 10. The maximum measured strain occurred in the outside flange near the base of the left-hand column, and was far in excess of the yield strain determined from the tensile test of the flange steel. This indicates that significant yielding occurred prior to failure.

The relationship between the horizontal force and the measured relative in-plane horizontal displacement of beam-column joint at the second story of the right-hand column for test frame 1 is shown in Fig. 12. ANSYS, one of the mostly widely used and accepted commercial finite element analysis program, was used. ANSYS Beam189 beam element was used for the analyses of test frame (Fig. 11). Five elements along the length of the beams and columns were used (Fig.11). and the obtained results from non-linear analysis were compared with the experimental data(see Fig.12).

Fig.10. Local buckling at the base of the left-hand column for frame 1

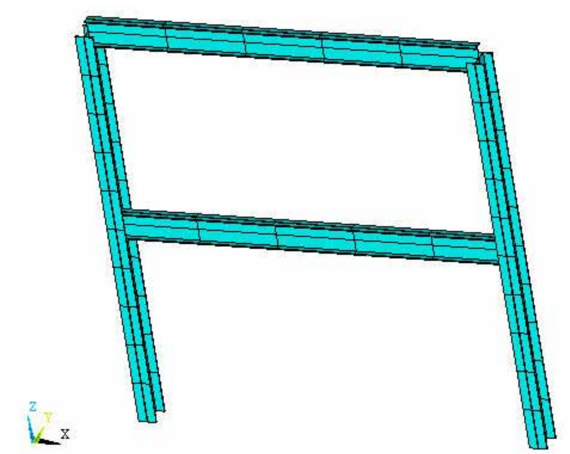


Fig. 11. finite element model and mesh of frame 1

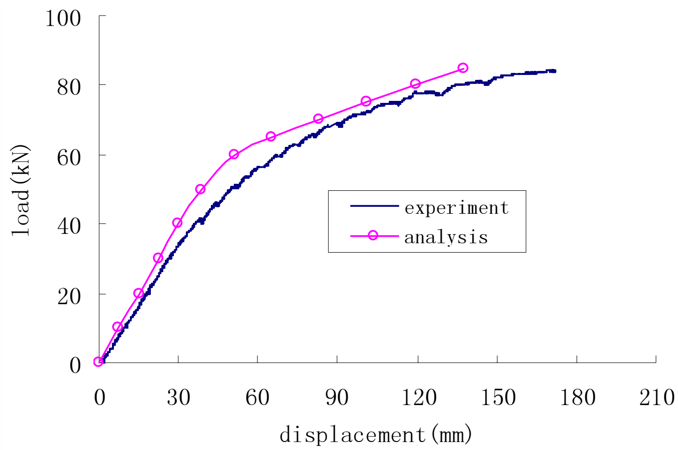


Fig.12. Comparison of horizontal load–displacement curves for beam-column joint at the 2nd story level of the right-hand column of frame 1

Test frame 2(without AAC infilled wall, cyclic loading)

The two identical repeated and reversed horizontal loads are applied at the beam-column joint at the first and second story level of the left-hand column in x-direction. The loading scheme for experiment on frame 2 is shown, in Fig. 13, in which H denotes the horizontal load in the *x*-direction and Δ denotes the horizontal displacement in the *x*-direction. The finite element model is the same as frame 1.

The hysteretic horizontal displacement curves for beam-column joint at the 2nd story level of the right-hand column obtained, respectively, by theoretical calculation and measurement are compared in Fig. 14. It is found that the theoretical predictions agree with the experimental measurements satisfactorily.

Test frame 3(with AAC infilled wall, static monotonic loading)

The loading scheme of test frame 3 is the same as that of test frame 1.

At a load of 40 kN per horizontal actuator the mortar between first story wall and floor girder began to crack and separate each other as the load increased. At a load of 65 kN per horizontal actuator the mortar between second story wall and first story steel beam began to crack and separate each other as the load increased. At a load of 101 kN per horizontal actuator a large crack appeared on the first story wall and at a load of 137 kN per horizontal actuator the frame began to unload indicating that the maximum capacity of the frame had been achieved. Light inelastic local buckling was observed at the base of the right-hand columns. The maximum measured strain occurred in the outside flange near the base of the right-hand column, and was far in excess of the yield strain determined from the tensile test of the flange steel. This indicates that significant yielding occurred prior to failure.

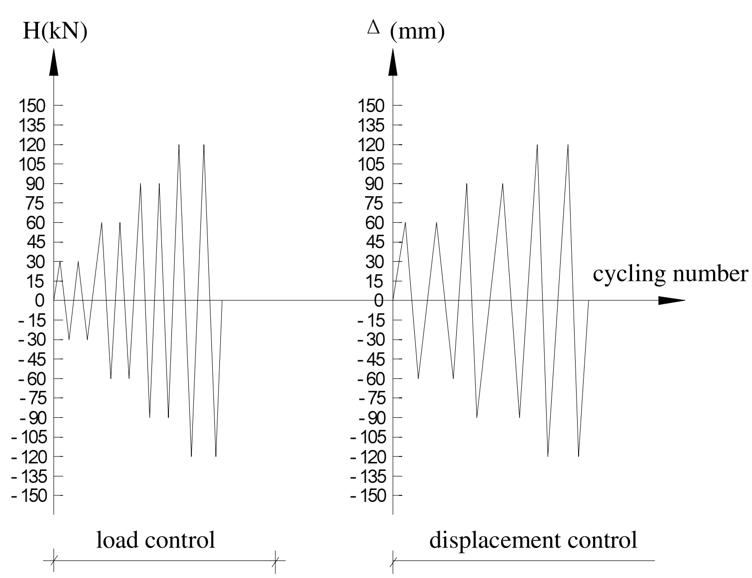


Fig. 13. Loading scheme for frame 2

The relationship between the horizontal

force and the measured relative in-plane horizontal displacement of beam-column joint at the second story of the right-hand column for test frame 3 is shown in Fig. 16.

In the finite element model, BEAM189 beam element was still used to model steel frame, SOLID65 element was used to model AAC infilled wall and COMBIN39 element was used to model the connection between steel frame and AAC infilled wall(Fig. 15).

The obtained results from non-linear analysis were compared with the experimental data(see Fig.16).

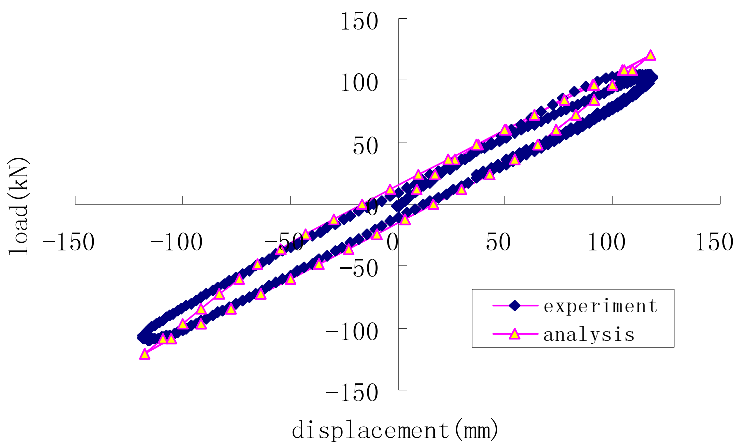


Fig.14. Comparison of horizontal load–displacement curves for beam-column joint at the 2nd story level of the right-hand column of frame 2

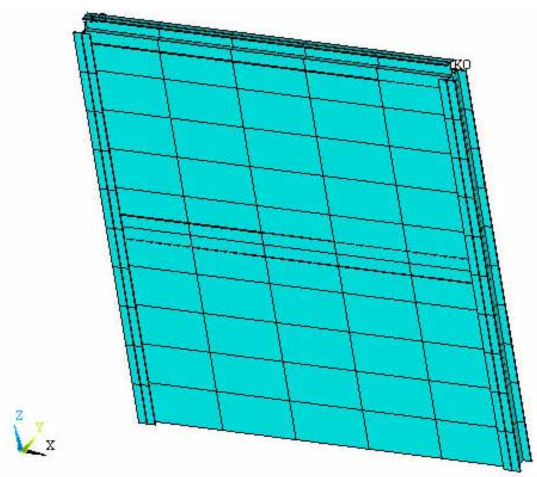


Fig. 15. finite element model and mesh of frame 3

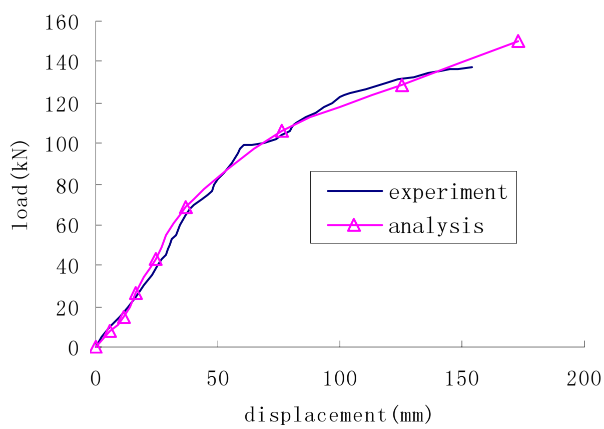


Fig.16. Comparison of horizontal load–displacement curves for beam-column joint at the 2nd story level of the right-hand column of frame 3

Test frame 4(with AAC infilled wall, cyclic loading)

The loading scheme of test frame 4 is the same as that of test frame 2, and the finite element model is the same as frame 3.

Although the column base was intended to be rigidly connected, the rigidly bolted connection cannot be achieved fully in some situation. So the semi-rigid connection is accounted for during the theoretical analysis. The obtained results from non-linear analysis were compared with the experimental data(see Fig.17).

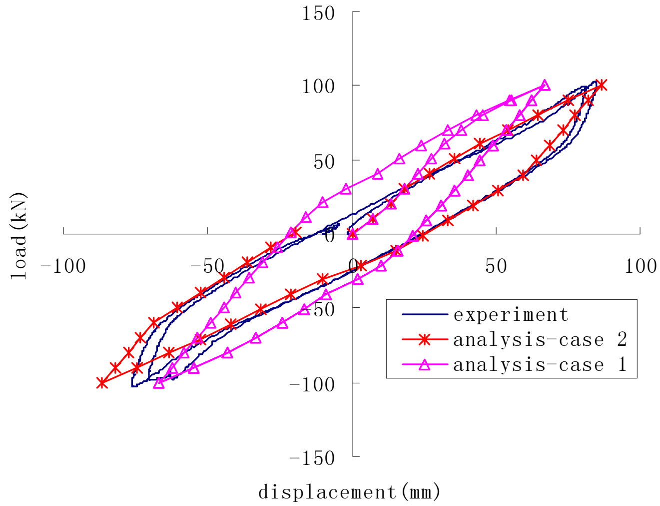


Fig.17. Comparison of horizontal load–displacement curves for beam-column joint at the 2nd story level of the right-hand column of frame 4
Case1:ignore column base rotation
Case2:consider column base rotation

Comparisons of results

Results with and without AAC infilled wall

In order to see the effect of AAC infilled wall on the load-carrying properties of steel frames, Fig.18 and Fig.19 are shown as follows. The experiment results showed that the ultimate load carrying capacity and stiffness of steel frame with AAC infill was 60% and 50% higher than that of steel frame without AAC infill, respectively, which shows the effect of the AAC infill.

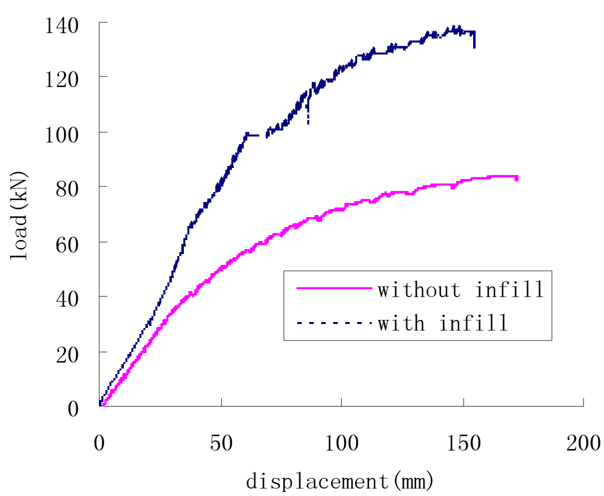


Fig.18. Comparison of horizontal load–displacement curves between frame 1and frame 3

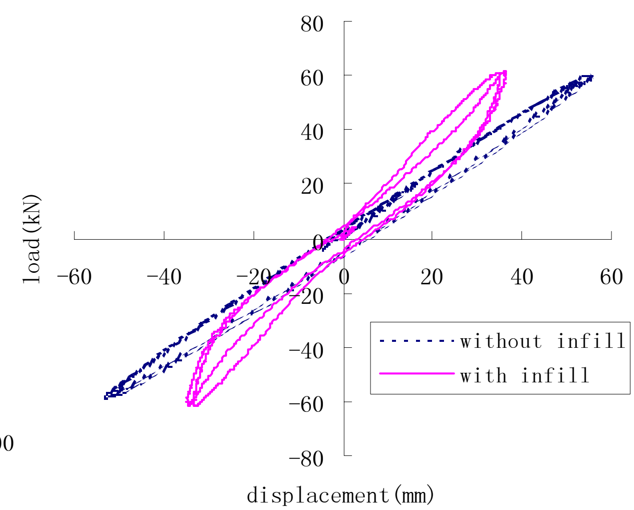


Fig.19. Comparison of horizontal load–displacement curves between frame 2and frame 4

Comparison between monotonic and skeleton curve

Skeleton curve is the envelope line of peak points of hysteretic curves of every load class, which can reflect the strength and stiffness of a structure. Fig.20 is the comparison of monotonic and skeleton curve of steel frame with and without AAC infill.

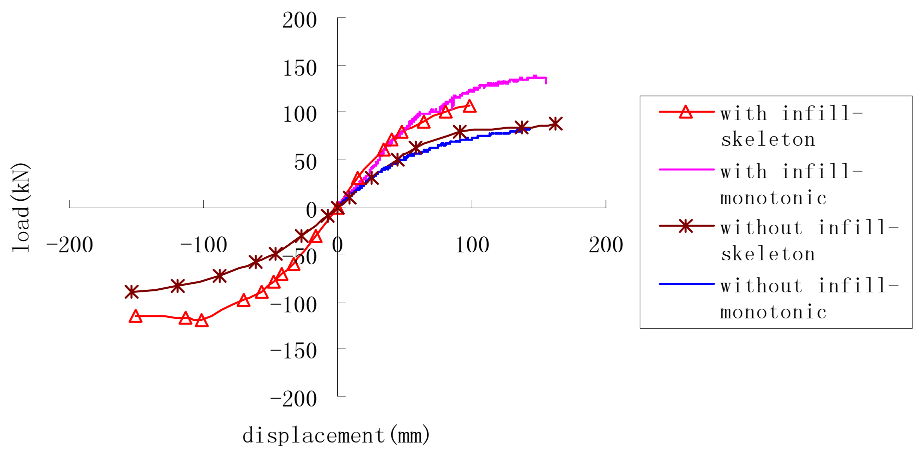


Fig.20. Comparison of monotonic and skeleton curves

CONCLUSIONS

The results of large-scale tests on four steel frame specimens with or without AAC infilled wall are presented in this paper. The load-displacement curves of the four frames are provided. It is found that the theoretical calculations agree with the experimental results satisfactorily. The AAC infill can enhance the strength and stiffness of steel frames to a large degree. It is appropriate to consider the influence of AAC infilled walls on the structural behavior of steel frames in the design of steel frames with AAC infilled wall in future.

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