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Seismic performance analysis of wedge-shaped Castellated portal frame

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Abstract: In order to study the seismic performance of wedge-shaped light steel castellated portal frame, the finite element analysis software Abaqus is used to simulate the seismic behavior of the portal frame with a single span hexagonal hole with a span of 24m. The influence of the opening ratio and the distance between the first hole of the near column and the end to the column edge on the hysteretic curve, skeleton curve, stiffness degeneration, ductility and energy dissipation capability are analyzed and the ultimate destructive form is also obtained. The results show that under the low cycle reciprocating load, the castellated light steel portal frame forms the plastic hinge on both sides of the structure near the first hole, and the structure loses its carrying capacity. The greater the opening ratio is, the lower the ultimate bearing capacity is, and the stiffness degeneration is more notable, ductility and energy dissipation are worse. The distance between the first hole of the near column and the end to the column edge has great influence on the ultimate bearing capacity, stiffness degradation and ductility. The greater the distance is, the better the ultimate bearing capacity and the ductility are.

1 Introduction

With the development of economy, the concept of green building is getting more and more popular. Light steel structure, as an important symbol of low-carbon environmental protection, has been widely used in the supermarket, civil buildings, sports venues and other buildings. Portal frame structure is a commonly used structural form [1]. According to the mechanical characteristics of portal frame structure, the member is designed into wedge shape, which satisfies the force of the structure and saves the material [2-4].

Castellated steel members have advantages of bending stiffness and remarkable economic benefit [5-7]. Wedge-shaped castellated members have the common advantages of wedge-shaped members and castellated beams. They are applied in portal frame structure, which is not only beautiful in appearance but also convenient for layout of equipment and pipelines, and has good application prospect.

At present, some scholars have made some achievements in the research on the mechanical properties and seismic behavior of castellated steel frame [8]. But the research of the equivalent section castellated light steel portal frame is only in the initial stage, and the long-span portal frame structure often uses the wedge-shaped section. This paper will use the finite element analysis software Abaqus to analysis the seismic performance of a single span hexagonal hole wedge-shaped beam portal frame with a span of 24m. The influence of the opening ratio and the distance of the first hole to the column edge on the seismic behavior of the structure is analyzed, which provides reference for the design and application of the castellated light steel portal frame.

2 Finite Element Analysis model

2.1 Model design

The single span hexagonal hole wedge-shaped beam portal frame with a span of 24m is designed. The slope is 1:15, the height of the cornice is 6.9m, and the hinge pin is used. The cross-section dimensions of the rigid frame are shown in table 1.

Table1. Sectional dimensions of castellated beam portal frame

Dimension parameter （mm）	The bottom of the column	The top of the column	Beam end section	Beam cross section
Depth of section	300	700	858	390
Flange width	240	240	180	180
Flange thickness	8	8	6	6
Web thickness	6	6	5	5

The specimen number is named in the form of a beam, such as a model named "2460-h", in which "24" represents a span of 24m, "60" represents the opening ratio of the castellated beam as "h2/h1=60%", and "H" represents the distance of the first hole of the rigid frame to the column edge as "S=1H", the parameters are shown in Table 2 and Figure 1.

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Table2. Dimensional parameters of castellated portal frame

Specimen number	Opening ratio h_2/h_1	The distance of the first hole S/mm	The first hole side length L/mm	Hole pitch d/mm
2450-H	50%	858	230.0	363
2455-H	55%	858	254.0	400
2460-0.5H	60%	429	284	404
2460-H	60%	858	278	374
2460-1.5H	60%	1287	270	414
2460-2H	60%	1716	278	370
2465-H	65%	858	300	415
2470-H	70%	858	324	382

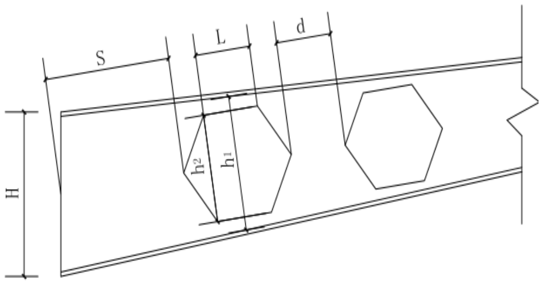


Figure 1. Size parameter of castellated beam

2.2 Material parameters and unit selection

In the finite element model of the wedge-shaped section portal frame structure, the steel grades of each member are Q235B, the elastic modulus is 2.06×105Mpa, Poisson's ratio is 0.3. The constitutive model of steel uses double slash model, and strengthen section modulus take 0.01 times of elastic modulus. The unit type uses C3D8R (eight connections six plane) linear reduction integral element, and the rigid frame connection all uses the welding.

2.3 Loading method

Vertical load: Roof constant load is $0.25kN/m^2$, roof live load is $0.5kN/m^2$, and column distance is 6m, the load action mode shown in Figure 2. First, put the monotonic static loading on the structure, the yield displacement of the cellular beam portal frame under horizontal load is carried out, and then the low cycle reciprocating loading process is given. When the structure enters yielding, on the basis of yielding displacement, each level of displacement load increases 5mm, and each load cycle for one time, until the structure is destroyed.

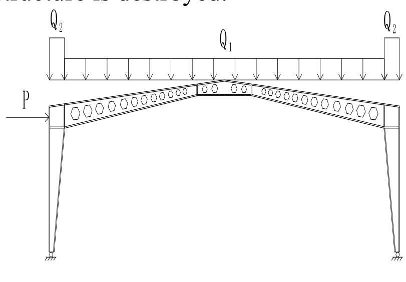


Figure 2. Model loading diagram

3 Simulation results analysis

3.1 Failure mode

The results of finite element analysis show that under the action of low cycle reciprocating load， the internal force change and the final failure form of the castellated beam portal frame under different parameters are similar. Taking rigid frame 2460-H as an example, with the increase of the amplitude of the horizontal displacement load, the lower flange of the beam at the first hole is first entered into yielding, and as the amplitude of the displacement load increases, the upper flange near the cross section is entered into the yielding. Finally the local buckling is produced by the two holes entering the full cross section yielding, two plastic hinges are formed. The rigid frame beams have obvious collapse under vertical load. The whole structure loses the ability to continue to withstand horizontal loads.

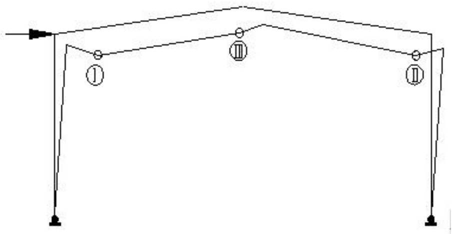


Figure 3. Failure mode analysis of castellated beam portal frame

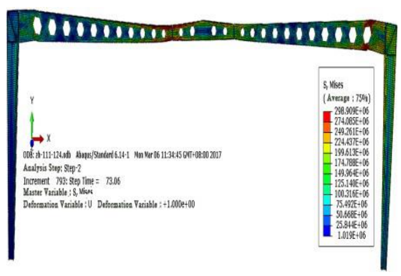
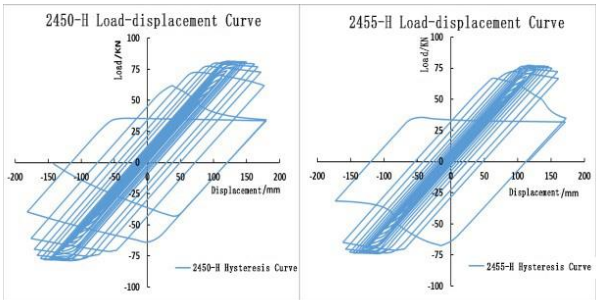


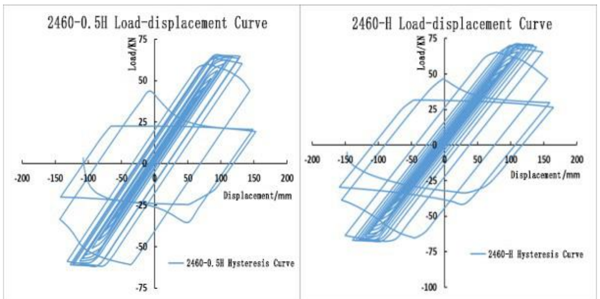
Figure 4. Stress cloud of the broken castellated portal frame

3.2 Hysteresis curve

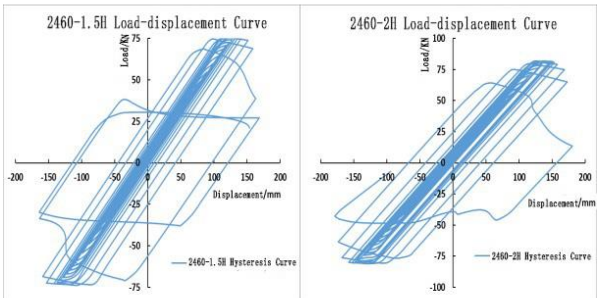
Hysteretic curve is the main basis for evaluating seismic performance of structures, and the hysteretic curves of each specimen are shown in figure 5. In the initial stage of displacement loading, the structure is in elastic phase, the hysteretic curves of each specimen are close to the coincident oblique line. After loading to the yield displacement, the horizontal section is present in the hysteretic curve of each specimen, the lower flange section of the beam at the first hole of the near-end is entered into yielding, it shows a fuller spindle and the cyclic loading continues. The ability of the structure to withstand the horizontal load decreases greatly and the structure loses the load capacity when the first hole of the beam yielded.



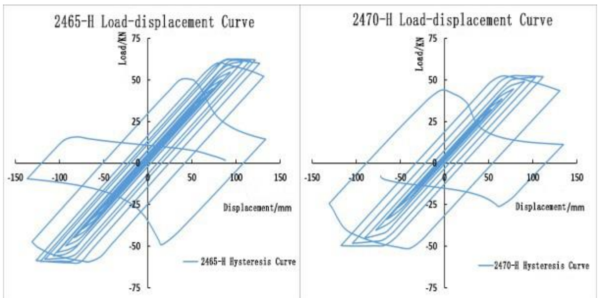
（a）2450-H （b）2455-H



（c）2460-0.5H （d）2460-H



（e）2460-1.5H （f）2460-2H

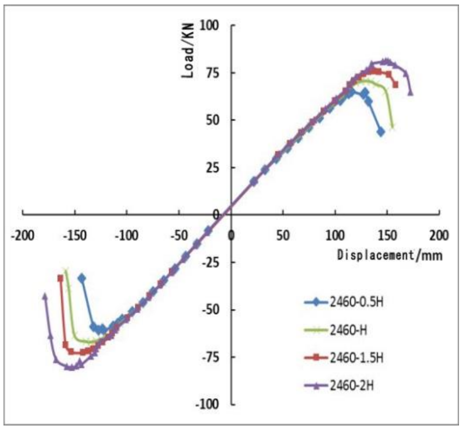


（g）2465-H （h）2470-H

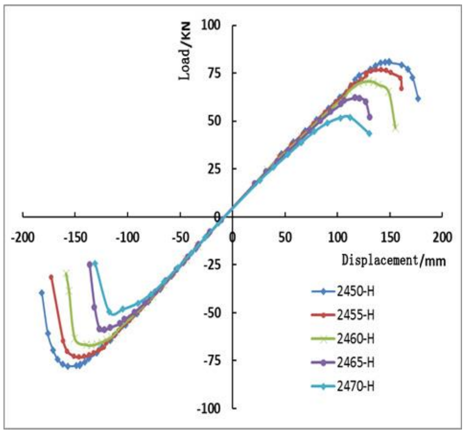
Figure 5. Hysteretic curve of castellated beam portal frame

3.3 Skeleton curve

The skeleton curve of the castellated portal frame with different parameters is shown in figure 6 (a) (b). At the beginning of loading, the skeleton curves of each specimen are straight lines and the structure is in an elastic stage. When the structure enters the plastic stage, the skeleton curve begins to diverge, reaches their peak load and then drops precipitously. It can be seen that the higher the opening ratio is, the lower the bearing capacity (peak load) of the structure is. The greater the distance from the first hole to the column edge of the near column beam is, the higher the bearing capacity of the structure is.



（a）The frame skeleton curve of different distance

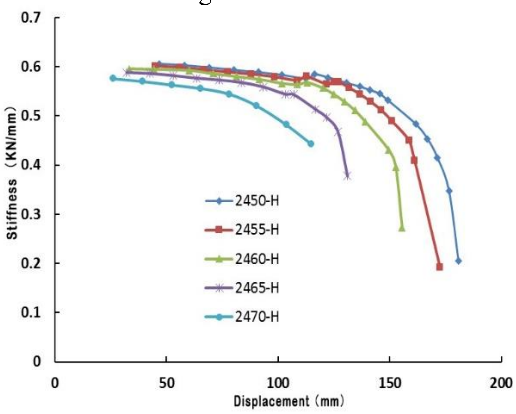


（b）Skeleton curves with different openings ratio

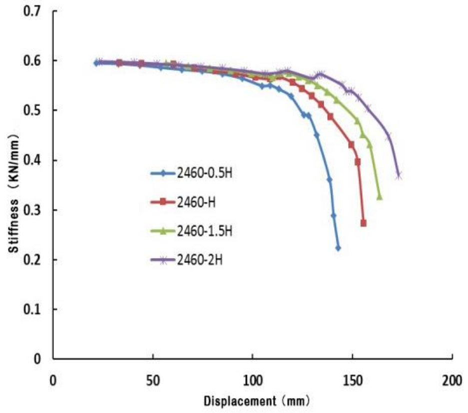
Figure 6. Comparison of skeleton curves

3.4 Stiffness degradation

Figure 7 (a) (b) gives the stiffness curves of each specimen, the opening ratio has a greater influence on the stiffness at the initial loading stage, and that the distance between the first hole and the column edge at the end of the near column has a small effect. After the structure enters the plastic stage, all specimens have obvious stiffness degeneration. The smaller the distance is, the more obvious the stiffness degeneration is.



（a）Stiffness degradation curve with different openings ratio



(b) Stiffness degradation curve of different distance
Figure 7. Comparison of stiffness curves of frames

3.5 Ductility

Table 3 gives the relative data of the displacement ductility coefficient of the finite element simulation, it can be seen that the higher the opening ratio is, the earlier the structure enters yield and the ductility performance is improved. The greater the distance between the first hole and the edge of the column is, the higher the ductility performance is.

3.6 Energy dissipation capacity

The equivalent viscous damping coefficient h_ε and energy dissipation coefficient E are used to express the energy dissipation capacity of the specimen [9]. The equivalent viscous damping coefficient h_ε and energy dissipation coefficient E under the peak load of each specimen are given in table 4. With the increase of opening ratio, the section of the castellated hole which forms the plastic hinge decreases gradually, and the energy dissipation is gradually weakened. The distance between the first hole and the column edge of the near column has little influence on the energy dissipation ability of the whole structure.

Table3. The ductility coefficient of frames

Model number	Yield displaceme nt /mm	Limit displacement /mm	Ductility factor
2450-H	117	165.53	1.41
2455-H	113	161.59	1.43
2460-0.5H	109	140.16	1.29
2460-H	111	159.96	1.44
2460-1.5H	113	163.88	1.45
2460-2H	116	170.52	1.47
2465-H	99	145.54	1.47
2470-H	85	128.35	1.51

Table4. The peak load energy dissipation coefficient of each frame

Model number	h_ε	E
2450-H	0.293	1.841
2455-H	0.237	1.488
2460-0.5H	0.203	1.275
2460-H	0.206	1.295
2460-1.5H	0.201	1.262
2460-2H	0.209	1.314
2465-H	0.193	1.215
2470-H	0.178	1.118

4 Conclusion

(1)Under the action of low cycle reciprocating load, castellated light steel portal frame has plastic hinge on both sides of the structure near the first hole. When the plastic hinge enters the full cross section, the rigid frame oblique beam has a large vertical displacement and the structure loses its carrying capacity.

(2) The opening ratio of the portal frame has great influence on the seismic performance. The higher the opening ratio is, the lower the ultimate bearing capacity is, the more obvious the stiffness degradation is. When the opening ratio is large, the damage occurs at the hole position. The specimen still has high bearing capacity and the ductility is relatively good after the peak load.

(3) Under horizontal load, the influence of distance for ultimate bearing capacity, stiffness degradation and ductility is relatively large, the influence on the overall energy dissipation capacity is relatively small. The greater the distance is, the better the ultimate bearing capacity and the ductility are. After the structure enters the plastic stage, the smaller the distance is, the more obvious the stiffness degeneration is.

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