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Investigation on Opening Sizes and Influencing Factors of the Connection with Opening on Beam Web of Steel Frames

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Abstract: The connection with opening on beam web is analyzed by Finite Element Program ABAQOUS. The optimal opening sizes and location are determined under the static loads. The factors to influence the formation of plastic hinge in beams and columns withstand static load are considered. Conclusions are drawn that the formation position is not only related with the web height h, but also with flange width b. The result provides us with a theoretical basis for specific engineering practice.

Keywords: Steel frame, web opening, plastic hinge, connections.

INTRODUCTION

It is considered as a new kind connection that the connection with opening on beam web, which is proposed on the basis of the damage of steel frame beam-column connections caused in earthquakes [1]. The new kind component can not only withstand brittle failure but save the steel when exposed to sudden loads. The basic idea of the paper is to out-shift the plastic zone which is originally located at the beam-column joints through weakening the nodes near the beam web, and protect the weld joints which connect beams with columns at the nodes through deforming the beam to consume the earthquake energy [2]. The type of beam with circular opening on the web can be used to make the indoor pipe-lines got through the inside of the web cavity, which can reduce the storey height and improve the economic benefits. In addition, the process of opening circular opening on the web of beam can be finished in the factory, therefore, the construction difficulty can't be increased and it is easy to control the quality. While, the method discussed is not widely used in engineering at present. On one hand, the current study on the topic is only limited to the range that circular opening on the web weakens the node but improves the ductility of the beam, while the sectional dimension of the beam, the pore size and location of aperture have not been specifically identified all, only the range of pore size and height of the beam web are given as below: the recommended pore size is between 0.55h-0.75h, the recommended location of the aperture is between 0.75h-1.55h, in accordance with the distance between hole center and the surface of column flange (h is the height of the beam web) .On the other hand, final conclusions on the factors that influence the forming location of plastic hinge have not drawn yet. In this paper, to determine the optimal aperture location and pore size of the beam with opening on web under static loads, the nodes are analyzed using Finite Element Program ABAQOUS. Under conditions that beams and columns withstand static loads, the influence of the selection of sectional dimension on the formation position of plastic hinge are analyzed. We draw the conclusions that the formation position of plastic hinge is not only related with the web height h, but also with flange width b.

1. THEORETICAL ANALYSIS

1.1. Theoretical Study About the Web Opening

Currently, The studies for stability of the web opening beam are mostly focused on cellular beams. Some scholars think that web opening may lead to global flexural-torsional buckling of beam, but Nethercot D A [3] had global flexural-torsional buckling experimental study about cellular beams. The results show that the instability of cellular beams is very similar to the one-sided instability of Soild-web Beams and Web openings almost have no effect on the one-sided buckling. Furthermore, after weakening of web opening beam, ratio of width to thickness of web and boundary conditions have changed. The critical buckling load of web and mutual constraint relationship between web and flange plate may have been changed [4]. Generally, flexural capacity of H-section steel beams is determined by flange section resistance moment W_f, while the shear capacity is determined by the area of web A_w. After weakening of web opening beam, the area of web A_w will be reduced. And its shear capacity will be reduced. Shear failure belongs to brittle failure. So it should be avoided in the design. According to finite element analysis, beam flange and shear equivalent area A_{vf} at the opening section can be expressed as [5]:

$$A_{vf} = t_f \times (0.375 t_f + t_w + 0.375 t_f) \times 2 \qquad (1)$$

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Where t_f —thickness of beam flange

t_w —thickness of beam web

1.2. The Failure Mechanism of Web Opening

According to internal force redistribution model about weakened zone of web opening which was proposed by Qing Shan Yang et al, we can obtain the following equation:

$$N_T = \frac{M_O}{2H_T}, V_T = \frac{V_0}{2}, M_{TL} + M_{TR} = V_T C_T \tag{2}$$

Where H_T —distance between two centroids of T-members

C_T —the length of the T-members

According to the equation, we know that possible failure modes of weakened zone of web opening have three modes as following:

(1) Shear failure. When V_T is more than shear capacity in its cross-section (T-members) that is the occurrence of such damage.

(2) Bending failure. When N_T is more than Critical buckling load in its cross-section (T -members), the beam opening is weakened.

(3) Vierendeel mechanism failure. In the combined effect of N_T and M_T, it is up to bending capacity and tension capacity of T –members. The four corners of weakened zone of web opening will form plastic hinges and it is the so-called vierendeel mechanism. Such damage appears in Fig. (**1**). For the connection with circular opening on beam web, the location of web opening is close to the beam end. In this point, bending and shear force are both the largest. The third form of damage is most likely to occur. If the third form of damage occurs, according to failure mechanism of the vierendeel mechanism, it is ductile failure.

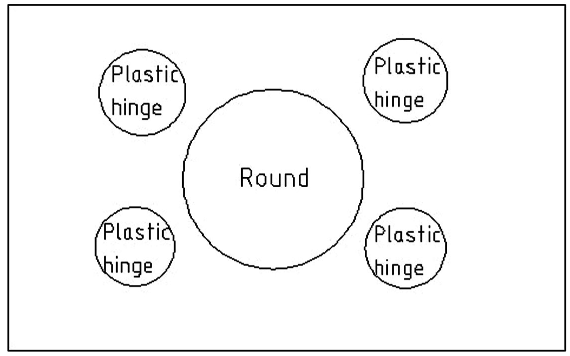


Fig. (1). Plastic hinges.

2. FINITE ELEMENT ANALYSIS OF BEAM-COLUMN CONNECTION

Finite element method is a very effective numerical method in structural analysis. In order to simulate the process of testing components and prepare for the next parameter analysis, this paper uses beams of different cross-sectional 7 and establishes models respectively. Calculated by the ABAQUS, we obtain the corresponding stress distribution and discuss the impacts on beam cross-sectional dimension to the strength of the connections and the impacts on the position and size of web opening beam to mechanical behavior and deformation performance of the connection.

2.1. Finite Element Model

Column section size is 450mm, * 300mm, * 12mm and *16mm, the length of column is 2000mm, cross-sectional size of beam B1 is 400mm, * 200mm, * 12mm and * 8mm, cross-sectional size of beam B2 is 400mm, * 300mm, * 12mm and * 8mm, length of the beam taken is 1800mm, stiffener dimensions size is 144mm, * 418mm and * 12mm, opening reference is 0.55h-0.75h,we take R = 125mm, the

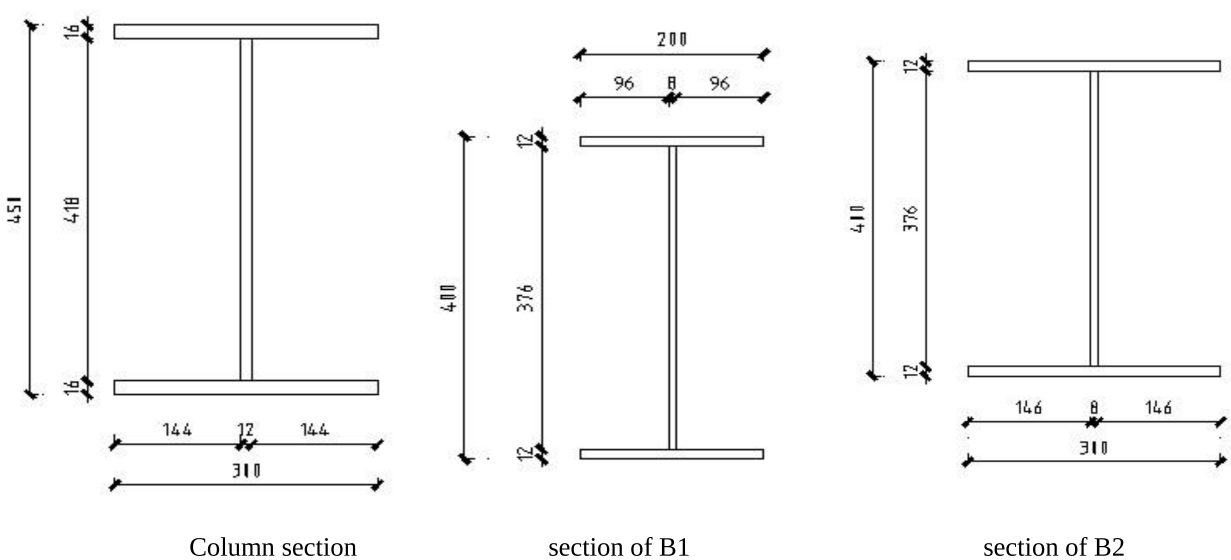


Fig. (2). Column section section of B1 section of B2.

location of opening reference is 0.75h-1.55h,we take B = 320mm. Cross-section is shown in Fig. (**2**).

All computational models use 3D solid element to simulate. As the focus is on the study of the stress and displacement at the beam and their connection, we intend to encrypted beam meshing. Beams, columns and stiffener all use tie connection, which is tally with the actual situation. Residual Stress of the welded connection is not considered. Beams, columns and stiffeners used are all ordinary Q235 steel, and we assume the materials are all isotropic materials. Elastic modulus of beams, columns and stiffeners are all 2.1×10^{11} pa, Poisson's ratio is 0.3, density of steel is 7800 $kg/m^{3.}$ Considered buckling deformation and plastic deformation can be more accurate response to the formation of plastic hinge on web, the yield stress and plastic strain are 3.45e8pa, 0mm and 4.5e8pa, 0.1mm respectively. Both ends of the column use fixed hinge supports. One end of the beam uses displacement loading, and the initial loading displacement is 0.005m (is not too large). Analysis step uses time loading step of ABAQUS, and the maximum and minimum loading steps are all 0.2s, loading time is 68s. Finite element model is shown in Fig. (**3**).

2.2. Calculation Results and Comparison

Stress nephogram calculation model is shown in Fig. (**4**), and the results show that B1 and B2 both appear as plastic hinges; plastic zone appears at top and bottom right of the opening section of the specimen. Plasticity development is focused on the edges of web opening and flanges. Plastic hinge is clearly away from the root node. Basically the root node is in the elastic state to achieve the purpose of the protection of the connections. The difference is that stress varies greatly in the plastic region, as shown in Table **1**, and the time difference of specimens with plastic hinge formed in the vicinity of the opening and yield stress of root node are not the same either, just as shown in Table **2**. The results showed that: The reason why the plastic hinges formation of beam B2 is later than B1 is that flange width of B2 and its stiffness increase. However, the time difference between plastic hinge formation of beam B1 opening and the root

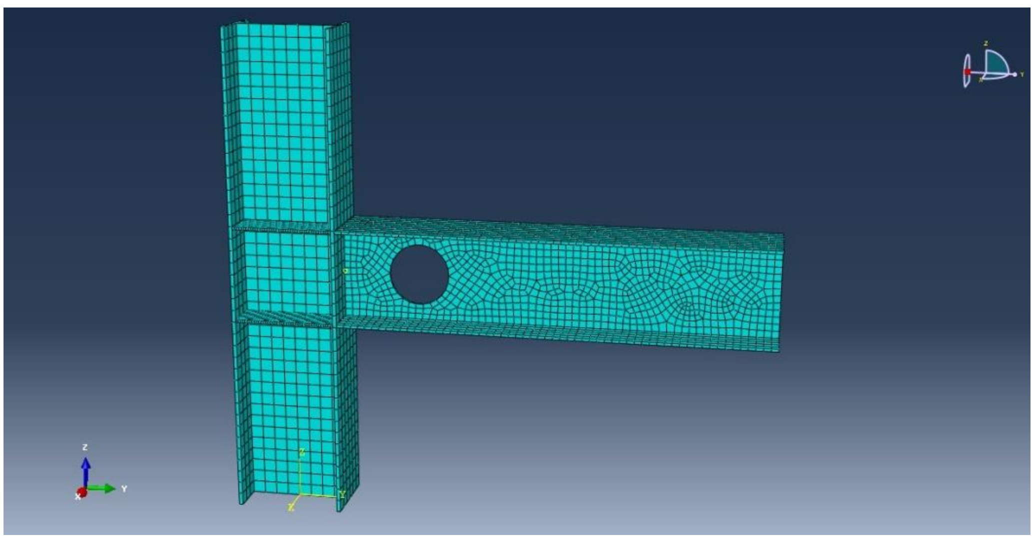


Fig. (3). Finite element model.

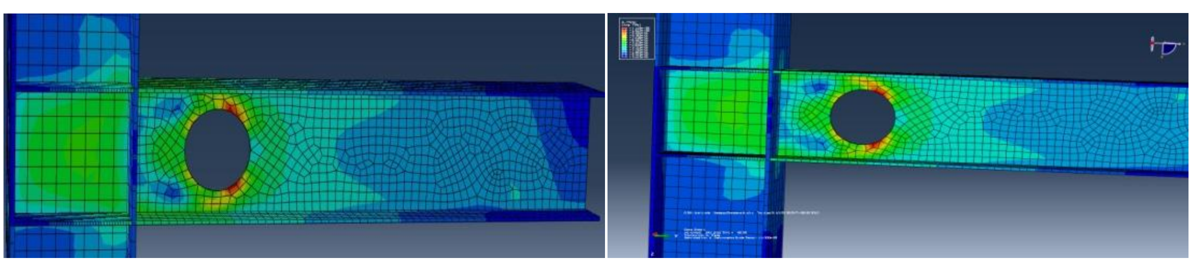


Fig. (4). Stress nephogram caculation model. (B1) (B2)

Table 1. The stress change table

	The Maximum Stress of Opening				Maximum Stress of the Root Node	
	Top right	**Bottom right**	**Top left**	**Bottom left**	**Top edge**	**Bottom edge**
B1	1190Mpa	1168Mpa	914Mpa	914Mpa	692Mpa	249Mpa
B2	746Mpa	760Mpa	550Mpa	583Mpa	372Mpa	249Mpa

node is $\Delta t = 5s$, but for B2, $\Delta t = 10s$. Under the same conditions, the root node formation of beam B2 is 5s later than beam B1. It is conducive to improve the ductility of the beam.

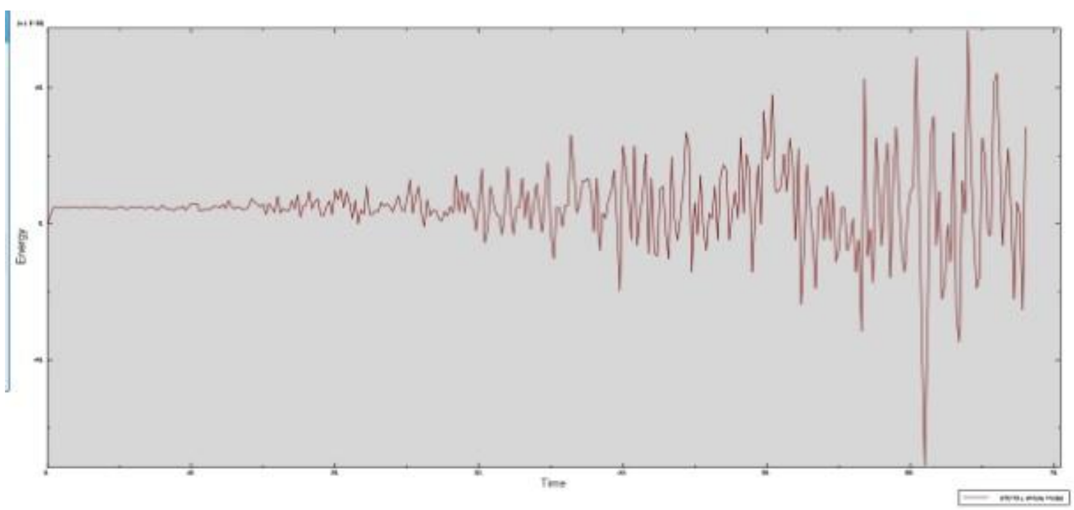
From the table, one can also compare that the flange of the beam cross-section increased by 1.5 times, which led to the stress of the opening decreased about 1.63 times and the stress of the upper surface of the flange of root node reduced 1.54 times. So increasing the width of the flange can effectively reduce the pore size and the stress of root node while saving material. At this situation, the ratio of web height of beam B1 and the width of flange is h/b=2. And the ratio of web height of beam B2 and the width of flange is h/b=1.3. If we continue to increase the width of the flange, node stiffness will increase, and however, it will greatly affect plastic hinge formation of the opening.

In order to determine the overall stability of the specimen and whether the energy loss of the specimen is too large or not, the overall energy of the specimen is compared in Fig. (**5**):

The results showed that : in terms of energy loss process, B1 and B2 didn't have too big changes ,which further proved that it's feasible to increase the width of the beam flange. Literature [6] have done similar experiments , indicating that the premise of ensuring connection strength. in order to facilitate the formation of plastic hinges, do not increase the yield strength of the material.

Table2. The stress change table

	Formation Time of Plastic Hinge at the Opening		Formation Time of Plastic Hinge at the Root Node	
	Start Time	**Maximum Time**	**Start Time**	**Maximum Time**
B1	10s	45s	15s	50s
B2	15s	55s	25s	65s



B1

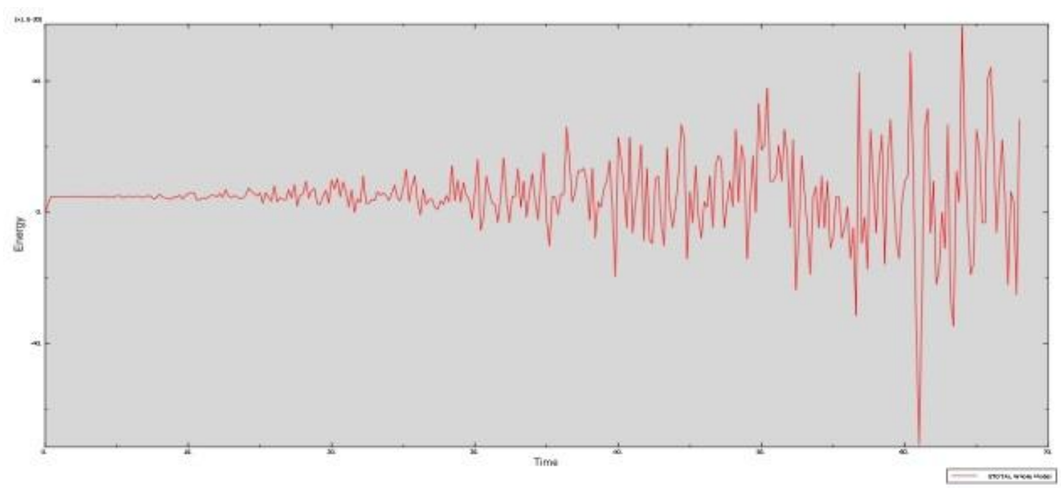


Fig. (5). Overall energy of the specimen. B2

3. CONCLUSIONS AND RECOMMENDATIONS

Through theoretical analysis and finite element analysis, in order to make sure the influencing factors of pore size, ductility analysis of beams and its connections**,** and section size of the beam, we can obtain the following conclusions:

(1) According to finite element simulation, we can get the main factors which affect pore size and location are: the Connection Form for Beam-column Joints (Welding or welding-bolt composite connection), web height of beam, strength grade of steel and width of beam flange.

(2) Using beam of the web opening can reduce the brittle failure of the connections effectively, improve the ductility of the beam, extend the time difference of plastic hinge formation and root node yielding, and thus play a role in protecting the connections.

(3) After comparing, plastic hinge of B2 is more effective than plastic hinge of B1. At this point, H / B = 1.33(beam B2), and H / B = 1.5(beam B1). In this case, B1 can also form very good plastic hinge. That is, when the plastic hinge is formed, the surface of the flange is close to the yielding. Its performance is in critical state. However, While continuing to widen the width of the flange surface such as H / B = 1, plastic hinges are formed on the webs, but flange does not have any signs of yielding. This situation does not meet the actual situation and has a waste of steel at the same time (H is the height of the web, B is the width of the flange) .

(4) According to the literature [6] and the study of this paper, we found that the formation of the beam plastic hinge has effect not only on the height of beam web, but also on the width of beam flange. Such a large number of software simulations show that: For the H-type steel, pore size is to meet 0.5-0.7H, and the distance between location of the opening and the surface of flange is 0.8-1.5H while meeting H / B = 1.1-1.5.

(5) This article does not consider that whether the welding residual stress has effect on the formation of the plastic hinge and beam sections.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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