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Steel frame collapse assessment method based on dynamic increase factor

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Research Paper

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Steel frame collapse assessment method based on dynamic increase factor

To study the laws of evolution of dynamic increase factors (DIF_s), relationship between the DIF_s and progressive collapse resisting capacity of a structure with web cleat joints under the column removal scenario, a refined finite element model is established based on an existing quasi-static test. The laws of evolution of DIF_s are studied for different loading type, beam height, and joint rotation stiffness. It was observed that the displacement-based dynamic increase factor (DIF_u) increases with an increase in the load level in elastic and elastic-plastic stages, and it decreases with an increase in the load level in the plastic stage. With an increase in structural damage, DIF_u reaches the maximum value when the frequency ratio is equal to 1 and decreases with a further increase in frequency and damping ratios. The load-based dynamic increase factor (DIF_p) is negatively corelated to the "arch compression effect" of the beam. Finally, a method based on DIF_u is proposed for judging the collapse of structures with web cleat joints. In addition, an improvement is provided for the design the web cleat joint. The improvement is proved to be reasonable and effective with the help of collapse evaluation method proposed in this study.

Key words:

progressive collapse, dynamic increase factor, collapse evaluation method, joint improvement, energy balance method

Prethodno priopćenje

Pengfei Wang, Xiaofei Wang

Metoda procjene kolapsa čeličnog okvira temeljena na faktoru dinamičkog povećanja

Kako bi se istražio razvoj faktora dinamičkog povećanja (eng. dynamic increase factors - DIF_s) i odnosa između DIF_s i sposobnosti otpornosti konstrukcije s priključcima izvedenim kutnicima na hrptu nosača na progresivni kolaps u scenariju uklanjanja stupa, na temelju postojećeg nazovi statičkog ispitivanja uspostavljen je rafinirani model konačnih elemenata. Zakonitosti razvoja DIF_s proučavaju se pri različitim vrstama opterećenja, visinama nosača i rotacijskim krutostima priključka. Utvrđeno je da faktor dinamičkog povećanja temeljen na pomaku (DIF_u) raste s porastom razine opterećenja u elastičnom i elastičnoplastičnom području, te se DIF_u smanjuje s povećanjem razine opterećenja u plastičnom području. S povećanjem oštećenja konstrukcije, DIF_u dostiže najveću vrijednost kada je omjer frekvencija jednak 1, opadajući s daljnjim povećanjem omjera frekvencije i stupnja prigušenja. Faktor dinamičkog povećanja temeljen na opterećenju (DIF_p) u negativnoj je korelaciji s "učinkom tlačnog luka" nosača. Konačno, metoda temeljena na DIF_u predlaže se za ocjenjivanje kolapsa konstrukcija s priključcima izvedenim kutnicima na hrptu nosača. U radu je ponuđeno i poboljšanje projektiranja priključaka izvedenih kutnicima na hrptu nosača koje se pokazalo razumnim i učinkovitim uz pomoć metode procjene kolapsa koja je predložena.

Ključne riječi:

progresivni kolaps, faktor dinamičkog povećanja, metoda procjene kolapsa, poboljšanje priključaka, metoda ravnoteže energije

1. Introduction

Since the partial collapse of Ronan Point apartment in 1968, many scholars and engineers have been studying the progressive collapse of building structures uninterruptedly. Progressive collapse of building structures refers to the initial damage caused by local failure of structures under an extreme event (such as strong earthquake, impact, explosion, fire, etc.) that develops in other parts of the structure due to internal force redistribution and eventually leads to partial or overall collapse of structures [1]. Following with the unconventional loads, the structural geometric composition changes suddenly and the vibration occurs. The progressive collapse of a structure is essentially a non-linear dynamic process. The real response of the structure can be obtained using non-linear dynamic analysis method. However, the analysis method is so complex that it is not suitable for practical engineering application. The dynamic response of the structure can be simplified as static by dynamic increase factor (DIF). In the research on progressive collapse, DIF is always a hot topic.

In 1964, Biggs [2] proposed that the dynamic analysis of a structure can be simplified by DIF_u which was used to reflect the relationship between static and dynamic responses of the structure. In addition, DIF_p was also proposed by researchers later for facilitating the design of structural components. Many scholars worldwide [1, 3-11] have put forth different views on this issue. In 2008, Hu and Qian [1] analysed the dynamic response of a single-storey plane steel frame under the column removal scenario using the simplified model and bar element model. The results showed that DIF_u in linear elastic state decreased with an increase in failure time and damping ratio, and the maximum value was 2.0; DIF_u in the plastic state was also related to the demand capacity ratio (DCR), which increased with an increase in DCR until the structural collapse. In 2009, Izzuddin and Nethercot [3] analysed DIF_p by energy balance method. It was pointed out that the DIF_p would increase with an increase in ductility if the catenary action of beams or membrane action were considered. USA design code DoD [4] fitted a curve of DIF_p vs plastic rotation angle based on a column removal test of a three-storey steel frame. It was considered that the DIF_p was related to the type of joints and development of plastic hinges, and the corresponding calculation formula was given. In 2010, Huo and Hu [5] studied the DIF_p in progressive collapse using the numerical analysis method. The results showed that the DIF_p were less than 2.0, and the dynamic response of the structure was very sensitive to the rotational stiffness of joints. In 2010, Tsai [6] studied the DIF_s based on the simplified model. The results showed that DIF_p decreased with an increase in ductility in the typical elastic-plastic structures; the DIF_u increased with an increase in load level. In 2011, Tian and Su [7] carried out a dynamic test of a double-span plane steel frame under the mid-column removal scenario. It was found that the DIF_p was in the range of 1.36 – 1.7. In addition, the DIF_p decreased with a decrease in beam stiffness caused by the load. In 2012, Naji and Irani [8] analysed the progressive collapse of steel frame: if the catenary action was not considered, the DIF_p may have increased as the ductility increased. However, when the ductility reached 12.0, the DIF_p approached 1.0. If the catenary action was considered, for a ductility value of approximately 4, an increasing ductility caused the DIF_p to decrease; however, after that point, the DIF_p increased. For a ductility value of 12.0, the value of DIF_p was approximately 2.0. As a result, if the catenary action was considered and ductility of the structure was high, using load factor of 2.0 was not conservative. In 2012, Tsai and You [9] studied the DIF_s in the progressive collapse of structure. The results showed that the DIF_u and DIF_p were different in the inelastic stage. The former was larger than 2.0, and the DIF_u curve was a downward concave. On the contrary, the latter was less than 2.0, and the curve tended to be a concave. In 2013, Liu [10] studied the DIF_s of the structure under the column removal scenario. It was considered that both DIF_u and DIF_p were approximately 2.0 in the elastic stage, and DIF_p would exceed 2.0 with the development of plastic hinges. In 2016, Xie et al. [11] conducted an experimental research on the DIF_p in the progressive collapse of steel frame. It was found that the DIF_p was equal to 2.0 using the static elastic method; while using the static elastic-plastic analysis method, the DIF_p was changing between 1.0 and 2.0. Deng et al. [12] carried out the theoretical derivation of DIF_s indicating that it was directly related to stiffness, damping ratio, and frequency ratio. In the literature [13], the theoretical formula of DIF_u was derived by Clough et al., which is a function of the damping ratio and frequency ratio.

In addition, many scholars had studied the relationship between material damage and dynamic characteristics of structural components. Based on the relationships between damping and strain and local damage and strain, the relationship between damage and damping was obtained with strain as the medium, and the corresponding formula was given by Xing [14]. Fu et al. [15] studied the constitutive relations considering damage and corresponding nonlinear dynamic equations for the laminated plate showing that the dynamic responses of the structures would change remarkably when the damage and damage evolution were considered. Wang et al. [16] considered that the dynamic characteristics of structures were dependent on mass, damping, stiffness, and their distribution in the structure. The dynamic characteristics of structures altered when these parameters and their distribution changed. Zhang et al. [17] studied the dynamic response of damaged components and dynamic behaviour of damaged materials numerically. It was concluded that when the frequency spectrum of damaged structure was down-shifted, the damping ratio of damaged materials was higher and the amplitude of response significantly increased. Additionally, they compared the curves of DIF_u vs frequency ratio (β) under different damping ratios (ξ = 0~0.8) in the case of damage (Ω = 0.4) and non-damage (Ω = 0) as shown in Figure

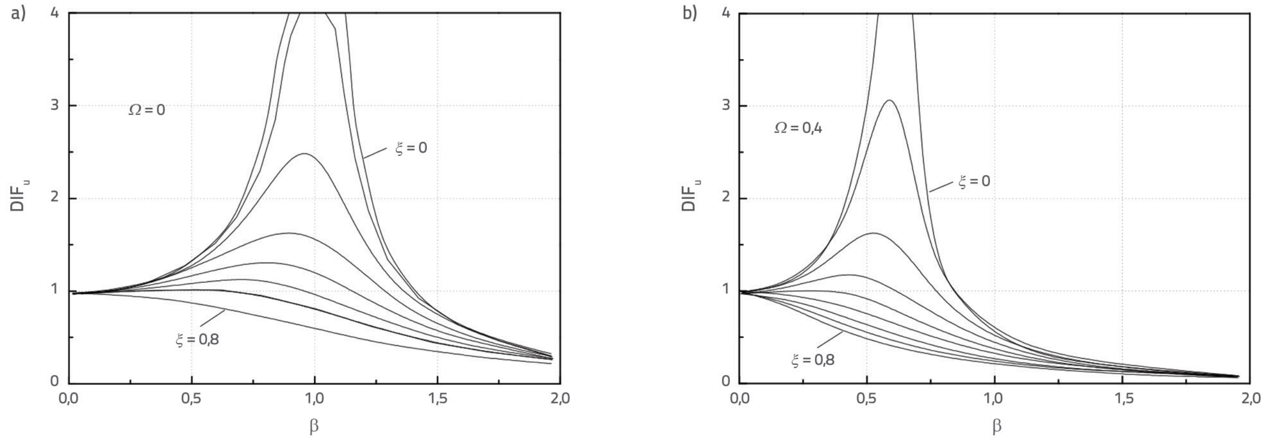

Figure 1. Relationship between DIF_u and frequency ratio of structure with different damping ratio (ξ=0~0.8) in the cases of non-damage and damage: a) In the case of non-damage; b) In the case of damage

1. Park et al. [18] considered the Park-Ang damage index as the collapse criterion. With an increase in cumulative damage of the structure, its ability to resist collapse decreased.

From the above, the effects of failure time, DCR, joint type, development of ductility and plasticity, damping ratio, frequency ratio, and damage on the dynamic response in the progressive collapse of structures were considered from the aspects of experiment, numerical simulation, or theory. At present, the research on the law of evolution of DIF_s in progressive collapse of structures is still not uniform especially the research on the DIF_u is relatively rare. In addition, it is found that the direct determinants of DIF are the dynamic performance parameters including the damping ratio and frequency ratio. According to previous studies [14, 16, 19] the damage or failure of a structure are also dependent on the damping ratio and frequency ratio. So, it is feasible that the DIF is adopted as a measurement to evaluate the damage or failure of the structure. Frequency ratio is defined as the ratio of applied loading frequency to the natural free-vibration frequency in the literature [13].

Based on the quasi-static collapse test of single-storey double-span plane steel frame with the web cleat joints under the concentrated load scenario conducted by Yang and Tan [20], the corresponding finite element model is established in this paper. Considering the influence of DCR, the development of plasticity, damping ratio, frequency ratio, and damage on the DIF_s, the DIF in progressive collapse is studied under different loading types, beam height, and joint rotation stiffness respectively, to analyse the laws of evolution of DIF_s and get the relationship between the DIF_s and progressive collapse resisting capacity of the structure with the web cleat joints under the column removal scenario, and to guide the structure design in a macro level. Finally, an improvement to the web cleat joint is developed.

2. Overview of existing tests

In the literature [20], the quasi-static collapse tests of single-storey double-span plane steel frames with different types of joints were conducted. The dynamic response in the progressive collapse process of steel frame with web cleat joint has been developed in this study for complementary research. In the test, UC 203x203x71 is for the column, UB 305x165x10 is for the beam, and L 90x8 is for the angle steel. With three 8.8 grade M20 bolts, the angle steel is connected to the beam web and column flange. Between the beam web and angle steel, the attached plate, which is 200x150x10, is designed. Stiffeners are designed in the panel zone of the joint. S275JR steel is used for angle steel and S355 steel for the other steels. The details of the joint are shown in Figure 2.

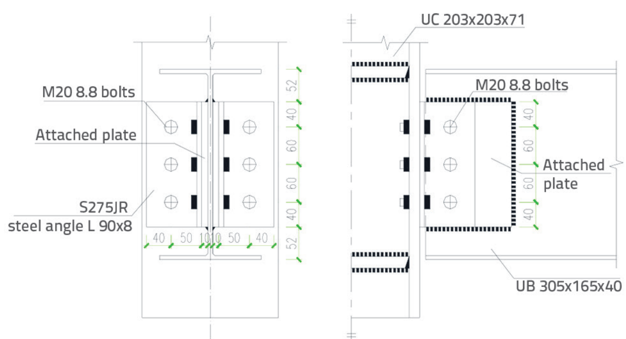

Figure 2. Details of joint [20]

The test device is shown in Figure 3. Assuming that the inflection point of the beam is in the middle of beam span, the left and right half-span beams and middle joint are taken as the research objects. The left and right ends of the specimen are hinged to the A-frame and reaction wall, respectively. Considering the spatial effect of the structure, lateral restraint systems are installed to limit the torsion and lateral displacement of the beam. H-frame with an actuator is installed above the joint as a lateral restraint system and loading system. A displacement-controlled point load is applied to the middle column using the actuator. Load, which is static, is applied under displacement control at a rate of 6 mm/min.

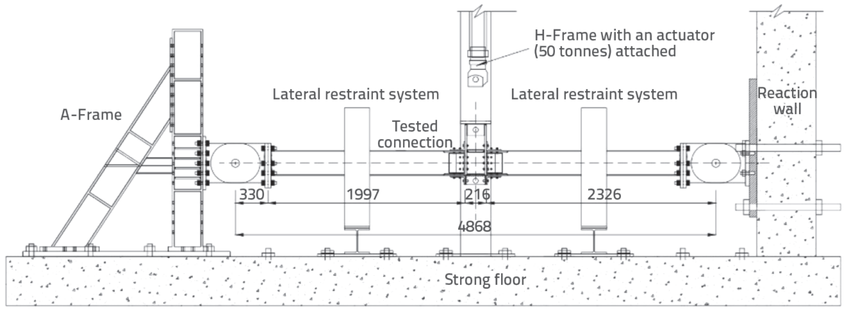

Figure 3. Test set-up (mm) [20]

The equivalent diameter of the bolt is 17.65 mm and preload for the bolt is 140 kN. The model is shown in Figure 4. For the applying of preload force of bolts in Abaqus, three analysis steps are established: first, a small preload force (0.01 kN) is applied to develop a steady contact in the simulation; second, normal preload force (140 kN) is applied; and third, the option 'fix at current length' is applied. The displacement-controlled point load above the failure column is applied in the fourth step of the analysis.

Both static analysis and dynamic implicit analysis methods are employed. In the dynamic implicit analysis, to obtain the equivalent static load-displacement curve, it is necessary to select an appropriate step time; that is, the time of column removal. The relevant collapse code stipulates that the duration of dynamic loading should not be greater than 0.1 times the natural vibration period of the remaining structure [22]. If the step time is prolonged in dynamic implicit analysis, dynamic response of the structure would be weakened. The comparison of simulation and experimental results is shown in Figure 5. The difference at the beginning may be due to the gaps in the simplified boundary constraints in the test. It can be considered that the simulation results are feasible. Besides, it also can be seen that the two simulation curves from different analysis methods coincide basically indicating that dynamic implicit analysis can replace static analysis. It should be mentioned that the displacement values in the dynamic implicit analysis represents the maximum displacement, hereinafter the same. Regarding the issue of FEM model on analysing dynamic performance of model structures, it would be illustrated in section 5.4.

3. Establishment and verification of finite element model

In this study, the finite element software Abaqus is employed. Referring to the known experimental data [20] and existing homologous simulation [21], considering the structural symmetry and computational efficiency, a multi-scale semi-model structure with a web cleat joint is established. The geometric dimensions of all components are the same as those in the test. Based on the mechanical parameters of the material, Q345B steel is used instead of S355 steel. The yield strength of Q345B is 350 MPa, ultimate strength is 550 MPa, and elongation is 22 %. According to reference [21], the angle steel is divided into two regions including the heel of angle steel and remainder, and different material parameters are endowed in the two regions. The solid element (C3D8R) and beam element (B31) are employed. The solid element (C3D8R) is only used in the connection position, column, and local beam section near the joint. The beam element (B31) is used in the beam section at the far end of the beam. The approximate element size for the bolts and bolt holes in the solid element is 5 mm, and it is 10 mm for the rest of the model. About the contacts in the FE model, the contact between the bolt and bolt hole is the normal hard contact. The contact between the bolt cap and steel plate and that between the angle steel and steel plate adopt both the tangential coulomb friction model and normal hard contact, and the friction coefficient is set as 0.5. The coupling constraints in the constraint command are used to define the beam solid element part and its beam element part.

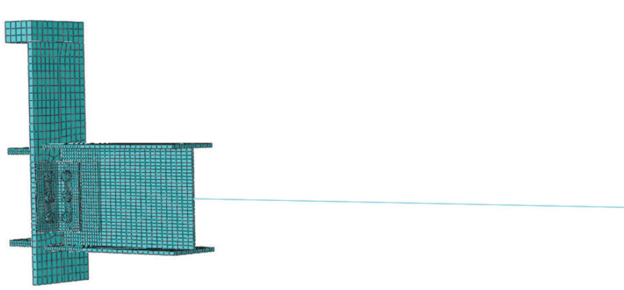

Figure 4. Finite element model

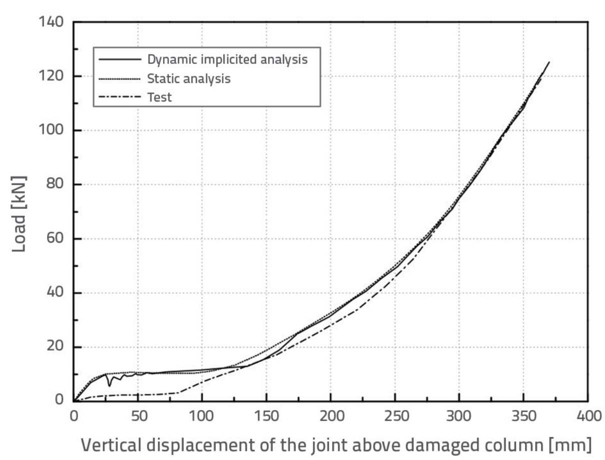

Figure 5. Verification of simulation result

4. Energy balance method

The energy balance method proposed by Izzuddin in 2008 [23] points out that the external work done by the applied loads is equal to strain energy of the structure. It is considered that the work done by the dynamic and static loads externally is equal if the structural response is the same as seen in Figure 6. It can be expressed by the mathematical formulae as follows:

$$p_d = \frac{1}{u_s}\int_0^{u_s} p du \qquad (1)$$

$$A_1 = A_2 \qquad (2)$$

Here, P_d represents the equivalent dynamic load corresponding to static load P_s; P_s represents the static load; u_d and u_s represent the displacements corresponding to P_d and P_s, respectively; A_1 and A_2 are the shadowed areas in the figure.

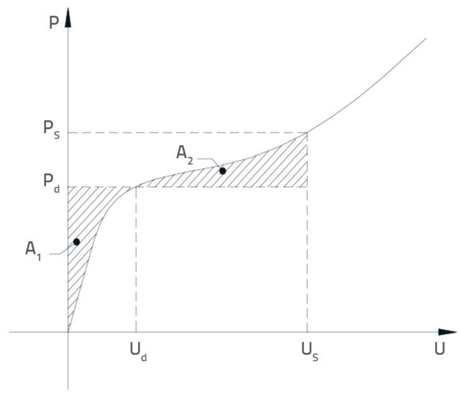

Figure 6. Explanatory chart for energy balance method

Based on the energy balance method, the dynamic displacement-load curve corresponding to the existing static displacement-load curve can be predicted. According to other relevant experimental results [15], the accuracy of results calculated by the energy balance method are within an acceptable range.
In addition, with the help of energy balance method, the theoretical evolution law of DIF_s with the increase of load level is roughly based on a general displacement-load curve as shown in Figure 7. From Figure 7, in the elastic stage (at the low load levels), the DIF is equal to 2.0. With an increase in load, the DIF_u increases and attains the maximum value at the first inflection point in the displacement-load curve. Then, it decreases with a further increase in load. As to the further development of DIF_u, the law of evolution of DIF_u might vary greatly due to the different types of joints and applied loads. It would not be described here.

5. Dynamic increase factors

In 1964, DIF_u was proposed by Biggs [2] to simplify the calculation of structural dynamic response. Later, DIF_p was also proposed by researchers for facilitating the design of structural components. At the same load level, DIF_u is the ratio of structural dynamic response to static response defined as following:

$$DIF_u = u_s / u_d \qquad (3)$$

DIF_p refers to the ratio of static load to dynamic load under the specified displacement. It is defined as follows:

$$DIF_p = P_s / P_d \qquad (4)$$

Here, u_s, u_d, P_s and P_d are the same as described in section 4.
Based on the FEM indicated in section 2, the DIF_s of structures under the column removal scenario are analysed using the dynamic implicit process analysis method using three aspects including the loading type, beam height, and rotation stiffness of connection, to guide the structural design at a macro level.

5.1. DIFs under different loading types

The concentrated and linear loads are applied respectively. The ultimate vertical displacement of joint in the simulation is equal to the maximum value of that in the test. The dynamic and static displacement time history curves for the two loading types under different load levels are obtained as shown in Figure 8. Then, the corresponding load-displacement curves are obtained as shown in Figure 9.
Combined with the damage phenomenon in the simulation in Figure 10, it can be shown that the key in the whole

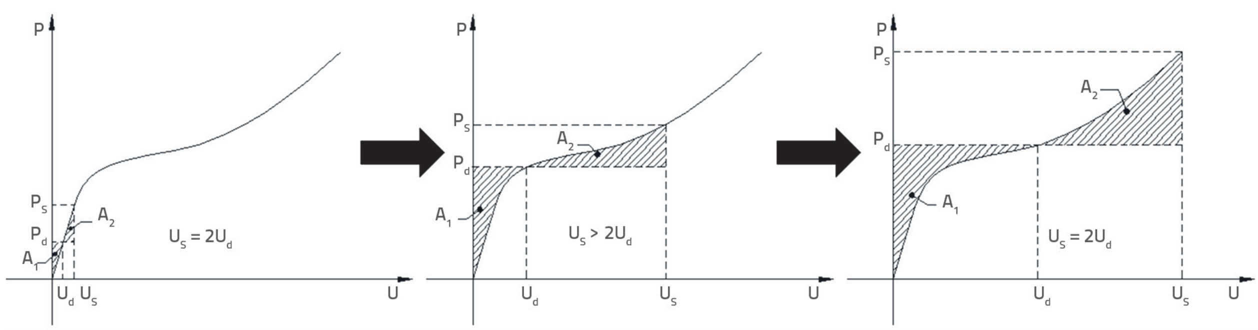

Figure 7. Theoretical law of evolution of dynamic increase factors

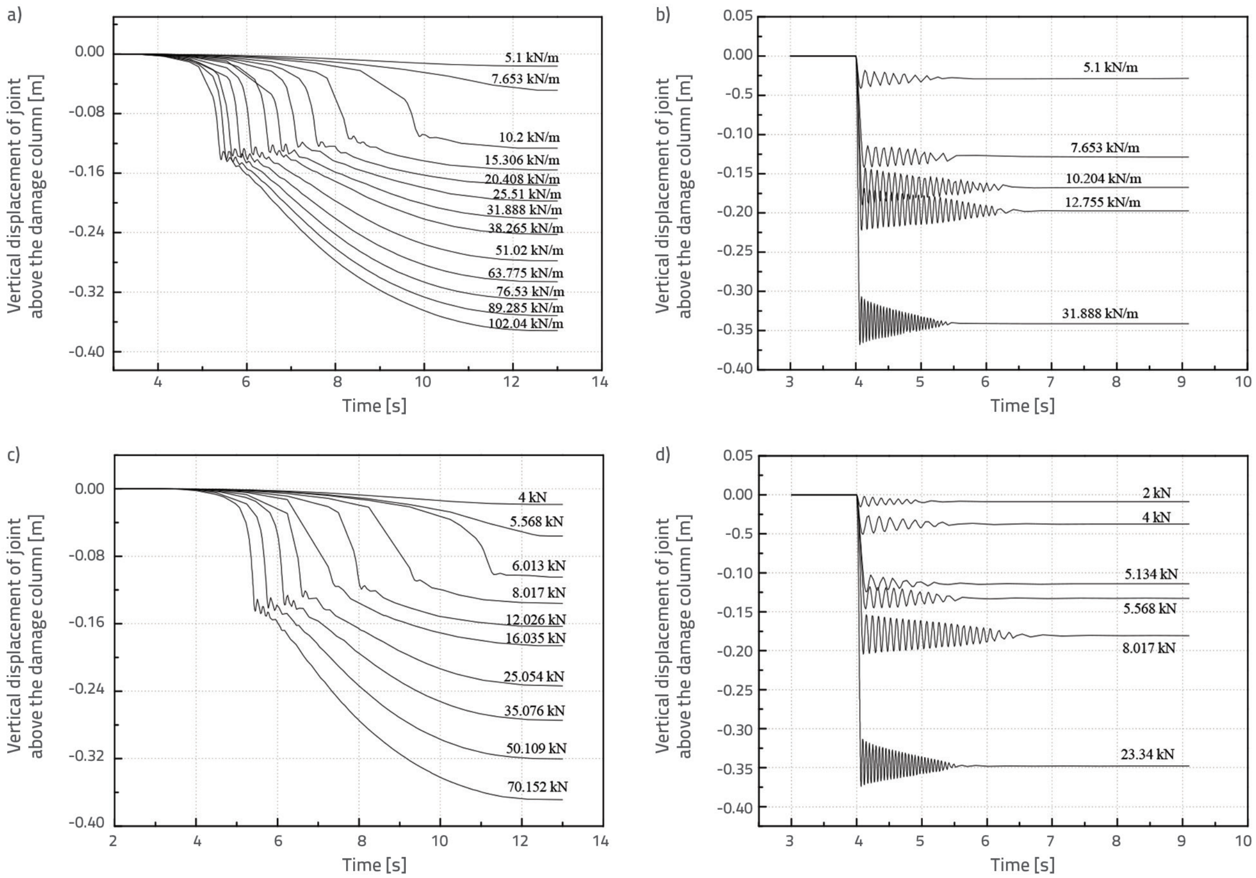

Figure 8. Displacement time history curves under different loading levels: a) Under static line loading condition; b) Under dynamic line loading condition; c) Under static concentrated loading condition; d) Under dynamic concentrated loading condition

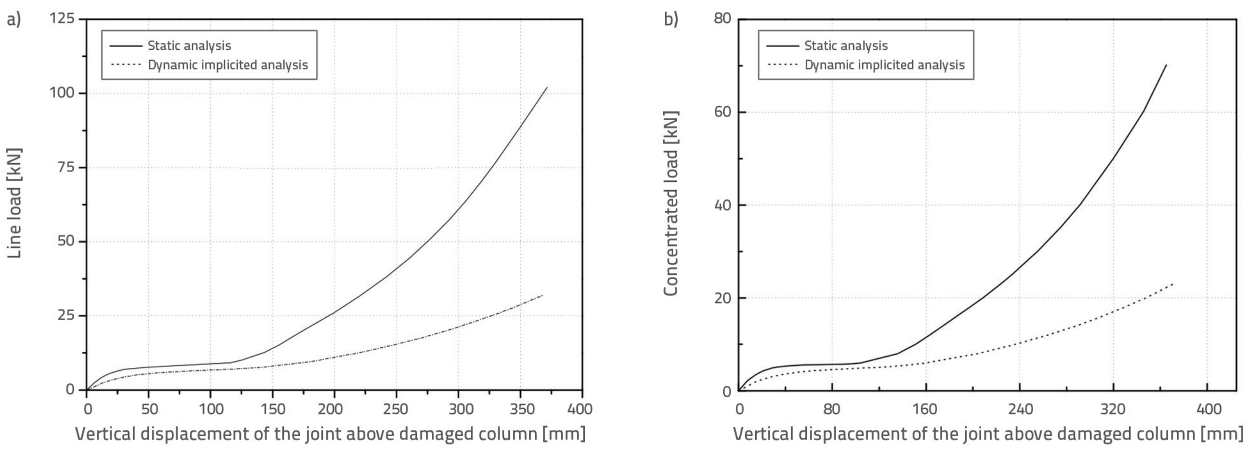

Figure 9. Displacement-load curves: a) Under line loading condition; b) Under concentrated loading condition

collapse process is the deformation of angle steels. Initially, the angle steels mainly bear the out-plane bending moment. Since the bending stiffness depends on the thickness of angle steels, it is relatively small. However, the tensile stiffness has not really intervened in the structural collapse resisting mechanism. Therefore, the anti-collapse stiffness of the structure at low load level is relatively small, which can be seen from the load-displacement curve. When the load reaches 7 kN/m or 6 kN, the yielding of out-plane bending occurs, which can be seen in Figure 9 or in Figure 11 (corresponding to the inflection point 1). Hereinto, Figure 11 provides a contrast between the beam axial force time history curve and load time history curve under the static linear load of 15 kN/m. With an increase in load, the plasticity of angle steels develops further. In Figure 11, it is obvious that a transformation from the 'compressive arch action' stage to 'catenary action' stage at the inflection point 2 for the beams exists. That is, the collapse resisting mechanism begins to gradually change from the out-plane bending resisting mechanism to tensile resisting mechanism at the inflection point 2 in Figure 11.

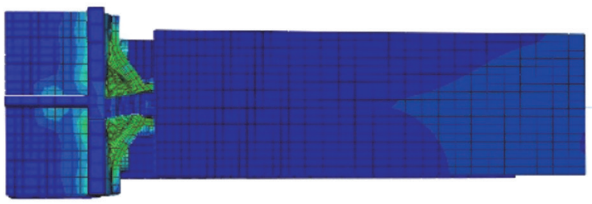

Figure 10. Damage phenomenon in simulation

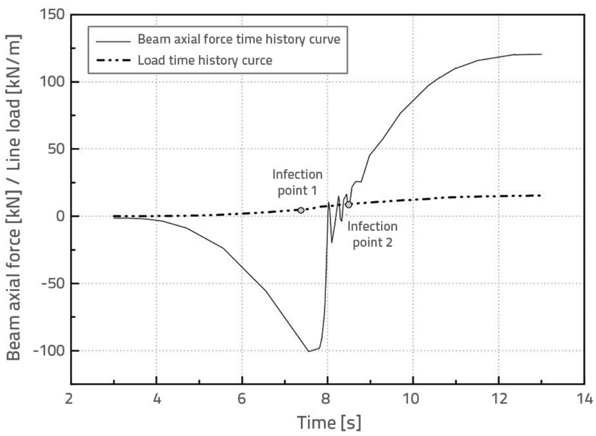

Figure 11. Time history curves of beam axial force and load

To facilitate the analysis, DCR is introduced and defined as follows:

$$DCR = P_0/P_u \quad (5)$$

In the formula, P_0 is the applied load and P_u is the collapse ultimate load.

Figure 12 shows the DCR-DIF curves under different loading types. Figure 12 indicates that there is an inverse correlation between DCR-DIF$_u$ and DCR-DIF$_p$ curves and a non-linear relationship between DIF$_s$ and DCR. At the low load level, the value of DIF$_s$ is approximately 2.0. For the web cleat joint, the DIF$_s$ increase with even a small increase in DCR, which is due to its small flexural stiffness. Initially, with the increase of DCR, DIF$_u$ reaches its maximum value; that is, when DCR is approximately 0.22 and decreases to its minimum value. Then, it increases slightly and finally decreases. However, DIF$_p$ reaches its minimum value when DCR is approximately 0.22; then, it increases with the increase of DCR until the collapse of the structure. In the process of increase of DIF$_p$, the sensitivity of DIF$_p$ to load level decreases gradually; that is, DIF$_p$ curve is not suitable to evaluate the progressive collapse resisting capacity of the structure.
From the perspective of loading type shown in Figure 12, the DCR-DIF$_u$ curves are basically the same especially at the high load level. As for the DCR-DIF$_p$ curves, the minimum value of DIF$_p$ under the concentrated load is 8.3 % smaller than the one under linear load. While under the high-level load, the value of DIF$_p$ under the linear load is slightly larger than that under the concentrated load.
On comparison of the results of DIF from the simulation and energy balance method under concentrated load in Figure 12, it is found that the results are basically the same. Under linear load condition, the maximum value of DIF$_u$ calculated by the energy balance method is 13 % less than that from the simulation. While at high load level, the difference disappears.
Thus, the DCR-DIF$_u$ curve is consistent with the development of plasticity of angle steel in the joint: before the out-plane flexural yielding of angle steel, the DIF$_u$ increases sharply with an increase in load level and decreases sharply with the development of plasticity of angle steel until the forming of plastic hinge. Then, the tensile stiffness of angle steel gradually plays a major role in the collapse resisting mechanism. In the new collapse resisting mechanism, the DIF$_u$ increases slightly due to the increase of load level and finally decreases slightly when the DCR is equal to 0.8. It can be inferred that the peak

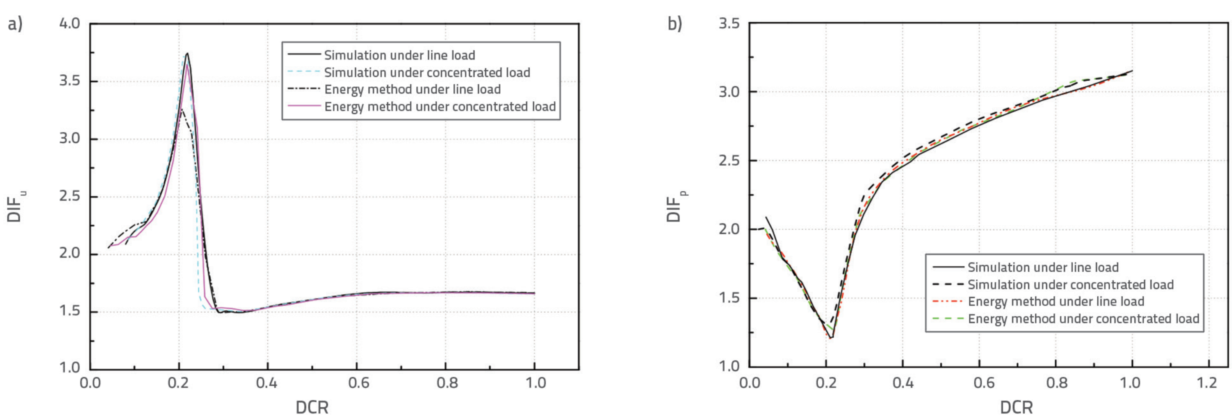

Figure 12. Comparison of DCR-DIF curves under different loading types: a) DIF$_u$; b) DIF$_p$

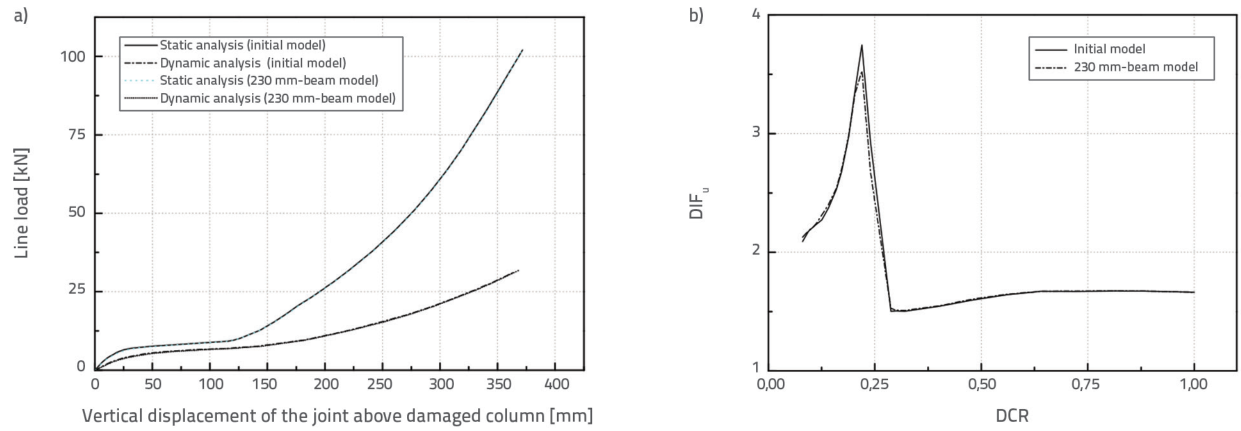

Figure 13. Comparison of the calculated results with different beam heights: a) Displacement-load curves; b) DCR-DIF$_u$ curves

in the DCR-DIF$_u$ curve corresponding to the tensile resisting mechanism could be used as the collapse critical point of structure. The applied load corresponding to the peak could represent the progressive collapse resisting capacity.

Then, the collapse evaluation method inferred above would be analysed from the perspective of material damage to further validate its rationality. Considering different collapse resisting mechanisms in the process of collapse of structure, the development of damage is divided into two types, including flexural and tensile. Each type of development of damage is corresponding to one DCR-DIF$_u$ curve. As the increase of DCR, the damage of structural components would develop gradually, following with the decrease of stiffness, increase of damping ratio and decrease of natural frequency [13]. Combined with the research in literature [17], a decrease in natural frequency results in maximum of DIF$_u$ when the frequency ratio is equal to 1.0; that is, the resonance of the structure. As the further development of damage with the increased DCR, the structure gets into the plastic stage and stiffness decreases sharply, which increases the damping ratio and frequency ratio. From Figure 1.0, once the frequency ratio exceeds 1, the increase in damping ratio and frequency ratio decreases DIF$_u$. Corresponding to each type of development of damage mentioned above, the DCR-DIF$_u$ curve shows a rising trend first and then falls. According to the analysis above, the yielding of structural component occurs at the peak in DCR-DIF$_u$ curve. For the progressive collapse research, the peak where the stiffness decreases sharply represents failure of corresponding collapse resisting mechanism. Combined with the existing test and FEM results, it is reasonable that the peak in the DCR-DIF$_u$ curve corresponding to the final collapse resisting mechanism could be taken as the collapse critical point of the structure. It can be considered that the peak in the DCR-DIF$_u$ curve corresponding to the tensile resisting mechanism could be used as the collapse critical point of the structure. The applied load corresponding to the peak could represent the progressive collapse resisting capacity.

However, DIF$_p$ is not sensitive to the plastic development. Combined with Figure 11 and Figure 12.b, the development of DIF$_p$ have a direct relationship with the development of beam axial force. The value of DIF$_p$ decreases with an increase in the compressive stress in the beam (or arch compression effect), and increases with a decrease in the compressive stress in the beam (or arch compression effect) until the failure of the structure.

5.2. DIFs with different beam heights

The influence of beam height on DIF under linear load condition will be analysed, which is intended to provide a reference for the design of the structure.

In this section, the beam height is specified as 230 mm corresponding to 303.4 mm in the initial model. Figure 13 shows the comparisons of the displacement-load and DCR-DIF$_u$ curves between initial model and 230 mm-beam model. It is found that the corresponding curves are the same in different model structures, which indicates that the beam height has no influence on the collapse performance of the structure with web cleat joints. This is because, the rotational stiffness which depends on the deformation and failure of angle steels is relatively small compared to the line stiffness of the beam.

5.3. DIFs with different rotational stiffnesses of joints

Based on the previous analysis, the thickness of angle steel is 7.0, 7.5, and 12 mm to study the influence of rotational stiffness of joint on DIF$_u$ and further verify the relationship between law of evolution of DIF$_u$ and progressive collapse resisting capacity of the structure with the web cleat joints. The DCR-DIF$_u$ curves, which are obtained by the same method as above, are shown in Figure 14.

In Figure 14, it can be seen that the influence of thickness of angle steel on DIF$_u$ is obvious. Under the flexural resisting mechanism: with an increase in thickness of angle steel, the improvement of out-plane stiffness of angle steel is small, thus having negligible influence on the natural frequency. Therefore, no significant difference exists in the demand capacity ratios corresponding to the peaks in the curves, which is dependent on the frequency ratio. With similar stiffness, the damping ratio increases with an increase in damping coefficient of the component, which increases with an increase in the thickness of angle steel. DIF$_u$

decreases with an increase in damping ratio [13, 17]. Under the tensile resisting mechanism: with an increase in thickness of angle steel, the improvement of tensile stiffness of angle steel is obvious resulting in an increase in natural frequency. The demand capacity ratios corresponding to the peaks in the curves increase with an increase in natural frequency. However, the influence of thickness of angle steel on the damping ratio is small and the maximum of DIF_u has no significant change. That is because, both the damping coefficient and tensile stiffness increase with the thickness of angle steel.

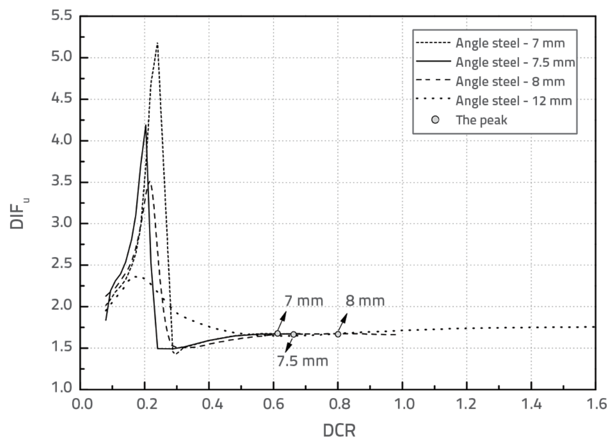

Figure 14. DCR-DIF_u curves with different rotational stiffnesses of joints

From Figure 14, the peaks in DCR-DIF_u curves corresponding to the last collapse resisting mechanism, move to the right with an increase in thickness of angle steel, and the one corresponding to 12 mm thickness angle steel still does not appear. Based on collapse evaluation method inferred in section 5.1, the peak in the DCR-DIF_u curve corresponding to the last collapse resisting mechanism, moves to the right with an increase of progressive collapse resisting capacity of the structure. According to the experimental results of Yang and Tan, it can be judged empirically that the ultimate load under the column removal scenario would increase with an increase in thickness of angle steel. For the 7, 7.5, and 8 mm angle steels, the ultimate displacements corresponding to the peaks are 0.293, 0.324, and 0.331 m, respectively; the ultimate loads corresponding to the peaks are 19.5, 21.1 kN/m and 25.5 kN/m, respectively. From the movement rule of peak in the DCR-DIF_u curves, it is considered that the FEM results are in good agreement with the collapse evaluation method.

Thereinto, the establishment of model structure with 8 mm angle steel is based on the existing test. The ultimate displacement in the simulation can be roughly specified as the one in the test, 0.365 m. The corresponding ultimate load in the simulation could be obtained in the displacement-load curve, 31.89 kN/m. The collapse ultimate load based on the collapse evaluation method is 25.5 kN/m and the corresponding DCR reaches 0.8. Combined with the relationship between the law of evolution of DIFu and development of damage, it is found that the progressive collapse resisting capacity of the structure could be predicted accurately by the collapse evaluation method proposed in this study.

From the failure mode of joints (fracture in the heel of angle steel) in the test, it is considered that the concentration of stress in the heel region of angle steel is the main cause and crack initiation point is the ends of angle steel. In the design, the ends of angle steel are far away from the bolts. The shape of angle steel is improved to weaken the stress concentration effect. The improvement of angle steel is shown in Figure 15. The simulation results of DIF_s are shown in Figure 16.

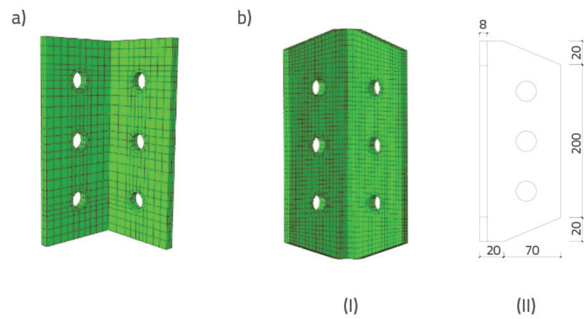

Figure 15. Geometry optimization of angle steel: a) Original; b) Optimized: (I) Entirety of angle steel; (II) Detail of single limb of angle steel

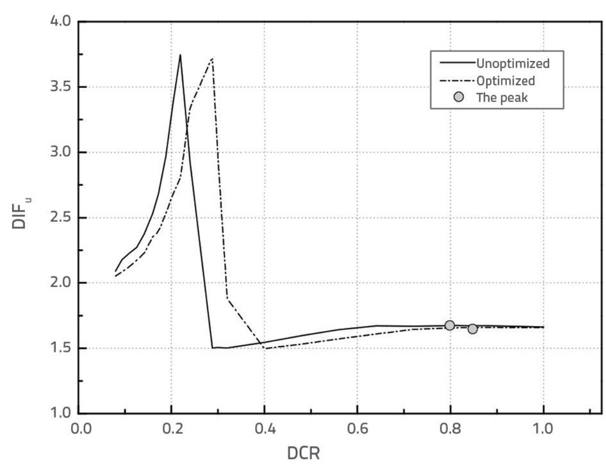

Figure 16. Comparison of DCR-DIFu curves before and after the optimization of joint

From Figure 16, it can be seen that the peak in DCR-DIF_u curve corresponding to the final collapse resisting mechanism moves to the right after the improvement of angle steel. Based on the DIF_u-based collapse evaluation method, the ultimate collapse resisting capacity of the structure is improved. The ultimate displacement and load corresponding to the peak in DCR-DIF_u curve under the final collapse resisting mechanism, are 0.342 m and 28.1 kN/m, respectively higher than those in the original model which are 0.33 m and 25.5 kN/m. The improvement for angle steel described in this study is reasonable and effective.

5.4. The influence of strain rate on DIF_u

The progressive collapse of structures is essentially a dynamic progress and the strain rate of material increases, which could motivate the change of constructive relationship of material. Based on the progressive collapse dynamic test results [24], it is found that the values of DIF are inexact in the static analysis and influence of strain rate on the law of evolution of DIF_u is negligible. The specific verification is as follows:

Based on the energy balance method, the DIFs with and without consideration of strain rate are calculated with the dynamic and static experiment results provided by Xie [24]. Figure 17 provides the comparison of DIF-displacement curves with and without consideration of strain rate.

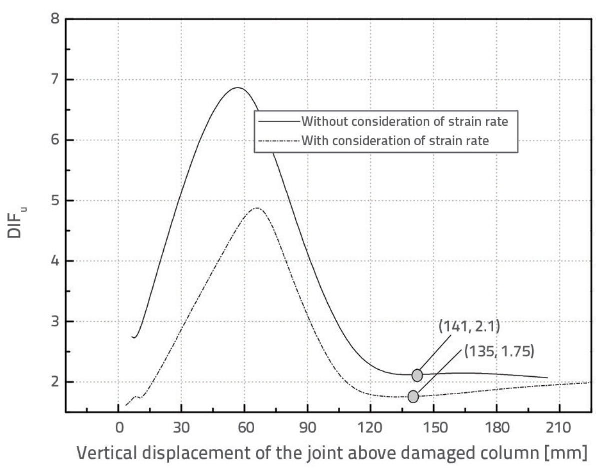

Figure 17. Comparison of DCR-displacement curves with and without consideration of strain rate

From Figure 17, the difference in DIFs with and without consideration of strain rate is very obvious. For the research on the value of DIF, the strain rate of material is crucial. But the laws of evolution of DIF with and without consideration of strain rate are almost synchronous especially for the inflection points in the curves. In this study, the laws of evolution of DIF is the central issue, and it could be acceptable that the strain rate of material is not considered.

In addition, the full-penetration welds between beams and columns are adopted in the beam-column joint in the test as given in literature [24], which belongs to the fully restrained moment connection. Here, the catenary action is ignored; that is, the resistance mechanism in the progressive collapse of structure is only one known as flexual resistance mechanism. For this fully restrained moment connection, the final point of the DIF-displacement curve in the stage of flexual resistance mechanism could be taken as the collapse criteria of structure, which is different from that for simple connections. Based on this collapse criteria of structure, it can be seen in Figure 17 that the failure displacements with and without consideration of strain rate are 141 and 135 mm, respectively. In the test conducted by Xie, the initial fracture of joint occurs when the vertical displacement of the joint above failure column reaches to 150 mm. It can be concluded that the DIF_u-based collapse evaluation method proposed in this study could not be fit only for web cleat joint.

6. Conclusion

In this study, a reasonable and refined finite element model is established based on Yang and Tan's existing test, which consisted of a single-storey double-span plane steel frame with web cleat joints. To guide the structural design at a macro level and considering the influence of DCR, plastic development, damping ratio, frequency ratio, and damage on the DIF, the law of evolution of DIF_s was analysed and studied under different loading types, different beam heights, and different joint rotation stiffness. The following conclusions are drawn:

- For the web cleat joint, the influence of loading type and beam height on the DIF_s was ignored. The influence of rotational stiffness on DIF_u was obvious especially under the flexural resisting mechanism.
- The law of evolution of DIF_u was analysed based on the plastic development of structural components and structural damage. It was found that DIF_u increased with an increase in load level in the elastic and elastic-plastic stages, and DIF_u decreased with an increase in load level in the plastic stage.
- Combining the beam axial force time history curve with the applied load time history curve, it was found that DIF_p is related to the development of the beam axial force; in other words, it is negatively corelated to the 'arch compression effect' of beam.
- According to the law of evolution of DIF_u, the DIF_u-based collapse evaluation method was proposed and verified based on the qualitative analysis and numerical simulation results.
- Based on the existing test, it was found that the influence of strain rate of material on the evolution law of DIF_u is small. And the DIF_u-based collapse evaluation method described in this study is not only fit for the web cleat joint.
- The improvement of web cleat joint was developed, and the reasonability and feasibility of improved connection were verified by the new collapse evaluation method.

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REFERENCES

[1] Hu, X.B., Qian, J.R.: Dynamic effect analysis during progressive collapse on a single-story steel plane frame, Engineering Mechanics, 26 (2008) 6, pp. 38-43, https://doi.org/10.1016/S1872-5791(08)60058-5.

[2] Biggs, J.M.: Introduction to structural dynamics, New York, McGraw-Hill, Inc., 1964.

[3] Izzuddin, B.A., Nethercot, D.A.: Design-Oriented Approaches for Progressive Collapse Assessment: Load-Factor vs Ductility-Centred Methods, American Society of Civil Engineers Structures Congress 2009, Austin, pp. 198-198, 2009.

[4] UFC 4-023-03: Design of buildings to resist progressive collapse, Department of Defence (DoD), Unified Facilities Criteria, 2013.

[5] Huo, J.S., Hu, C.L.: Dynamic effect research during progressive collapse of steel frame, Journal of Catastrophology, 25 (2010) S0, pp. 89-94, https://doi.org/10.3969/j.issn.1000-811X.2010.z1.020.

[6] Tsai, M.H.: An analytical methodology for the dynamic amplification factor in progressive collapse evaluation of building structures, Mechanics Research Communications, 37 (2010) 1, pp. 61-66, https://doi.org/10.1016/j.mechrescom.2009.11.001.

[7] Tian, Y., Su Y.: Dynamic response of reinforced concrete beams following instantaneous removal of a bearing column, International Journal of Concrete Structures and Materials, 5 (2011) 1, pp. 19-28, https://doi.org/10.4334/IJCSM.2011.5.1.019.

[8] Naji, A., Irani, F.: Progressive collapse analysis of steel frames: Simplified procedure and explicit expression for dynamic increase factor, International Journal of Steel Structures, 12 (2012) 4, pp. 537-549, Https://doi.org/10.1007/s13296-012-4008-0.

[9] Tsai, M.H., You, Z.K.: Experimental evaluation of inelastic dynamic amplification factors for progressive collapse analysis under sudden support loss, Mechanics Research Communications, 40 (2012), pp. 56-62, https://doi.org/10.1016/j.mechrescom.2012.01.011.

[10] Liu, C., Tan, K.H., Fung, T.C.: Dynamic behaviour of web cleat connections subjected to sudden column removal scenario, Journal of Constructional Steel Research, 86 (2013), pp. 92-106, https://doi.org/10.1016/j.jcsr.2013.03.020.

[11] Xie, F.Z., Shu, G.P.: Dynamic experimental study during progressive collapse of a steel plane frame, Journal of Building Structure, 37 (2016) 12, pp. 144-152, Https://doi.org/10.14006/j.jzjgxb.2016.12.018.

[12] Deng, L., Duan, L.L., Zou, Q.L.: Comparison of dynamic amplification factors calculated from bridge strain and deflection, Engineering Mechanics, 35 (2018) 1, pp. 126-135, https://doi.org/10.6052/j.issn.1000-4750.2016.08.0654.

[13] Clough, R., Penzien, J.: Dynamic of Structures, second edition, Computer and Structures, Inc., 2003.

[14] Xing, B.P.: Study on the relationship between the local damage and damping of concrete, 31 December 2013, Master, Yangzhou University, Yangzhou, China.

[15] Fu, Q.N., Yang, B., Hu, Y., et al.: Dynamic analyses of bolted-angle steel joints against progressive collapse based on component-based model, Journal of Constructional Steel Research, 117 (2016), pp. 161-174, https://doi.org/10.1016/j.jcsr.2015.10.010.

[16] Wang, S.S., Qiu, L., Xu, W.: Study on relationship between structural mass distribution, damage and dynamic response. Journal of Dynamic and Control, 8 (2010) 1, pp. 53-56, https://doi.org/10.3969/j.issn.1672-6553.2010.01.011.

[17] Zhang, W.H., Jin, Y., Chen, YM.: Behaviour of dynamic response for damaged materials, Journal of Vibration Engineering, 13 (2000) 3, pp. 413-425, https://doi.org/10.3969/j.issn.1004-4523.2000.03.013.

[18] Park, Y., Alfredo, H.S.: Mechanistic seismic damage model for reinforced concrete, Journal of Structural Engineering, 111 (1985) 4, pp. 722-739, https://doi.org/10.1061/(ASCE)0733-9445(1985)111:4(722).

[19] Fu, Y.M., Wang, Y.: Nonlinear dynamic responses of composite plates based on the damage model with internal state variables, Journal of Hunan University, 31 (2004) 6, pp. 70-74, https://doi.org/10.3321/j.issn:1000-2472.2004.06.016.

[20] Yang, B., Tan, K.H.: Experimental tests of different types of bolted steel beam-column joints under a central-column-removal scenario, Engineering Structures, 54 (2013) 1, pp. 112-130, https://doi.org/10.1016/j.engstruct.2013.03.037.

[21] Yang, B., Tan, K.H.: Numerical analyses of steel beam-column joints subjected to catenary action, Journal of Constructional Steel Research, 70 (2012) 7, pp. 1-11, https://doi.org/10.1016/j.jcsr.2011.10.007.

[22] GSA-2016.: Alternative path analysis and design guidelines for progressive collapse resistance, United States General Services Administration, Washington, DC, 2016.

[23] Izzudiin, B.A., Vlassis, A.G., Elghazouli, A.Y., et al.: Progressive collapse of multi-storey buildings due to sudden column loss: part I: simplified assessment framework, Engineering Structures, 30(2008) 5, pp. 1308-1318, https://doi.org/10.1016/j.engstruct.2007.07.011.

[24] Xie, F.Z.: Analysis and assessment and experimental research on progressive collapse of steel frame structure, 18 September 2014, Docter, Southeast University, Nanjing, China.