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Analysis of Energy Absorption Distribution for Circular Concrete-Filled Steel Tubular Members under Lateral Impact

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Analysis of Energy Absorption Distribution for Circular Concrete-Filled Steel Tubular Members under Lateral Impact

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Abstract. A nonlinear finite element model of the circular concrete-filled steel tubular (CFST) member under lateral impact is established based on the existing drop weight tests, and the accuracy of numerical simulation is validated by comparing with the test results. Then the segmented numerical model of the circular CFST member is divided evenly to obtain the distribution of energy consumption along its length. The results indicate that the prime areas of energy consumption for the circular CFST member are distributed at the impact position (within 1/6 of the effective length) and the support position (within 1/12 of the effective length). On this basis, the affect of impact position on energy absorption distribution is carried out to reveal the changes of the prime areas of energy consumption. The results of this investigation can provide a reference for the impact resistant design and damage reinforcement of circular CFST members under lateral impact.

1. Introduction

Concrete-filled steel tubular (CFST) members are widely utilized as main load-bearing components in high-rise and long-span building structures. So the serious engineering accidents may occur due to the damage or failure of CFST members caused by impact loads. Therefore, researchers have made a series of investigations on dynamic responses for CFST members subjected to lateral impact. Wang et al. [1] conducted drop weight tests on circular CFST members to study the affect of steel tube thickness and axial force on dynamic responses for CFST members under various impact kinetic energy. Deng et al. [2] investigated the impact resistance of circular CFST members with different spans based on drop weight tests. Wang et al. [3] conducted impact tests on the bottom of circular CFST columns, and proposed a simplified calculation method for impact resistance performance based on the energy consumption of CFST columns. Bambach et al. [4] established a calculation model of energy consumption for CFST members and hollow steel tubular members through impact tests and theoretical derivation. Wang et al. [5] investigated the deflection calculation of axially loaded CFST members subjected to lateral impact based on the single degree of freedom method.

Previous investigations [1, 3, 6] show that the CFST members under lateral impact have obvious local indentation at the impact position besides the global deformation, and the damage areas of circular CFST members under lateral impact have been studied in [7, 8]. However, for the whole impact process, the distribution of the local and global energy consumption for circular CFST members has not been fully investigated, and especially the research on the affect of impact position on energy absorption distribution is not clear enough. Therefore, the distribution of energy consumption along the length of circular CFST members remains to be further investigated.

In this investigation, based on existing drop weight tests, a nonlinear finite element model (FEM) of the impacted circular CFST member is established, and the accuracy of numerical simulation is validated by comparing its results with the test results. Then, the energy absorption distribution of circular CFST members is investigated through the segmented numerical model, and the prime areas of energy consumption in the local and global response stage for the steel tube and core concrete are determined respectively. On this basis, the affect of impact position on energy absorption distribution is carried out to reveal the changes of the prime areas of energy consumption for circular CFST members subjected to lateral impact.

2. FE analysis and simulation validation

2.1. FEM

Ref. [1] carried out a series of drop weight tests on circular CFST specimens with the fixed-sliding boundary conditions. The mid-span area of the specimen was impacted vertically by the drop hammer that fell freely along the slipway. The mass of the drop hammer was 229.8 kg, and the various impact energy was obtained by changing the impact height. The total length, effective length, outer sectional diameter and steel tube thickness of circular CFST specimens are 1800 mm, 1200 mm, 114 mm and 3.5 mm, respectively. The cube strength of concrete is 48.7 MPa. The yield strength and the elastic modulus of steel are 298.0 MPa and 201.0 GPa, respectively.

The FEM of the circular CFST member is established through the numerical simulation software LS-DYNA, as shown in Figure 1. The drop hammer is simulated by the rigid block with the size of $30\text{mm}\times 80\text{mm}\times 100\text{mm}$, and the support device is simulated by the rigid sleeve. The eight-node solid element with single point integral is utilized in the FEM of the circular CFST member. The keyword "*Contact Automatic Surface to Surface" is utilized to simulate the contact between the drop hammer, the rigid sleeve and the circular CFST member. The contact surface of the steel tube and concrete is set as common node, and the slip between the steel tube and concrete is not considered. The different initial velocity of the drop hammer is defined by the keyword "*Initial Velocity Generation".

In this paper, Mat_Concrete_Damage_REL3 material is utilized to simulate the concrete. The strain rate effects of concrete material are typically reflected by the dynamic increase factor (DIF), including the DIF of compressive strength recommended by the Comite Euro-international du Beton (CEB) and the DIF of tensile strength modified by Malvar [9]. The material model Mat_Plastic_Kinematic with the characteristics of elastic-perfectly plastic is utilized to simulate the steel tube, and the Cowper-Symonds equation [10] is utilized to reflect the strain rate effects of the steel tube.

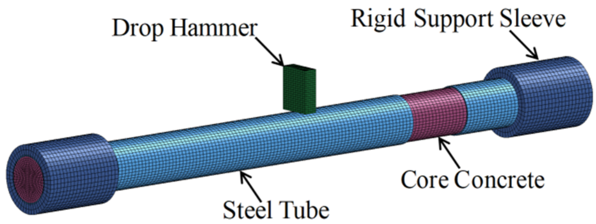


Figure 1. FEM.

2.2. Simulation validation

The above FE analysis method is used to simulate the test conditions [1], as shown in Table 1. It can be seen from Table 1 that the errors of residual deflections between the numerical simulations and drop weight tests are kept within 5%. The comparisons of damage modes for circular CFST members between the simulations and tests are shown in Figure 2. It can be seen from the effective strain (Von-Mises) obtained by numerical simulations that the damage of circular CFST members mainly occur at the impact position and in the support regions, which is consistent with the test results. In summary, the FEM established in this paper can well simulate the impact dynamic responses of circular CFST members, so the accuracy and reliability of the numerical simulation mentioned above can be validated.

Table 1. Comparisons between simulation results and test results.

Number	Impact height (m)	Impact energy (J)	Residual deflection (mm)		δ_{FEA} / δ_{tested}	Damage mode
			Test result δ_{tested}	Simulation result δ_{FEA}		
DZF23	5.0	11260	63.78	62.50	0.98	Deformation
DZF26	7.0	15764	87.20	83.70	0.96	Cracking

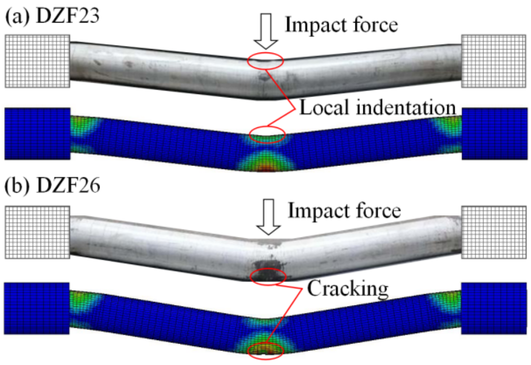


Figure 2. Comparisons of damage modes.

3. Energy absorption distribution

The distribution pattern of the internal energy for circular CFST members along the length can well reflect the energy absorption distribution of the members, which can provide some useful reference for damage assessment and local reinforcement in engineering application. However, the current impact test conditions can not directly measure the energy absorption distribution of circular CFST members, and the conventional entirety FEM can only obtain the energy consumption history with time. In view of this, the numerical model which has been validated above is segmented in this investigation, and then the energy absorption distribution along the length of the circular CFST member is obtained by extracting the internal energy of each segmented part. The simulation conditions are set as: the outside diameter, steel tube thickness and effective length of the circular CFST member are 114 mm, 3.0 mm and 1200 mm, respectively; the mass and impact velocity of the drop hammer are 50.0 kg and 24.0 m/s, respectively; the cube strength of concrete is 50 MPa and the yield strength of steel is 360 MPa; the boundary condition and impact position are the same as the tests [1]. The segmented numerical model of the typical circular CFST member is established in LS-DYNA, as shown in Figure 3, and the segmentation degree of the numerical model can be as fine as 1/120 of the effective length of the member. Thus, the energy absorption distribution along the length of the typical circular CFST member can be revealed as shown in Figure 4. It can be concluded that:

(1) At the instant after the impact starts, the energy consumption area of the circular CFST member is concentrated in the range of l/12 at the impact position (where l represents the effective length of the member). In the peak period of impact force (i.e. the local response stage), the energy consumption of the circular CFST member at the impact position is mainly borne by the concrete in the range of l/12, while the energy consumption of steel tube is relatively low. This is mainly due to the local response of the circular CFST member (such as local depression or local buckling) which leads to the concrete crush at the impact position, and then resulting in the increase of energy consumption of concrete.

(2) The energy consumption during the period from the peak of impact force to the end of impact (i.e. the global response stage) is the prime energy consumption process of the circular CFST member, and the energy consumption areas for the circular CFST member are distributed at the impact position (within 1/6 of the effective length) and the support position (within 1/12 of the effective length). The energy consumption of steel tube is higher than that of concrete, which is mainly due to the steel tube material develops a large tensile deformation in the global response stage, so that the steel tube is at a higher energy consumption level.

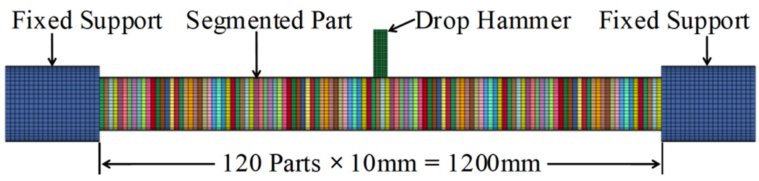
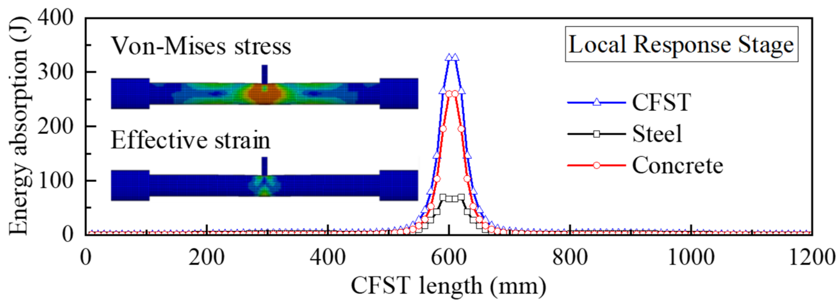
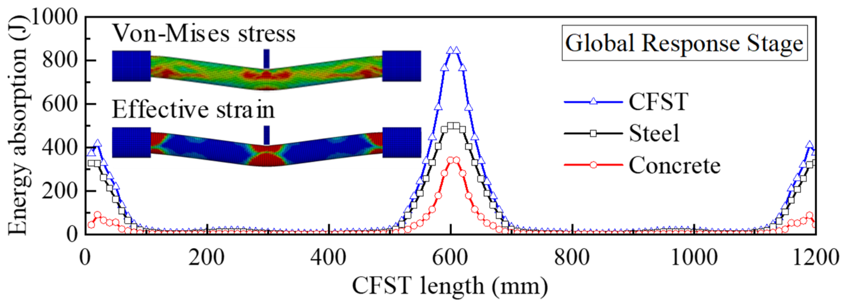


Figure 3. Segmented numerical model of the circular CFST member



(a) Local response stage



(b) Global response stage

Figure 4. Energy absorption distribution along the length of the circular CFST member.

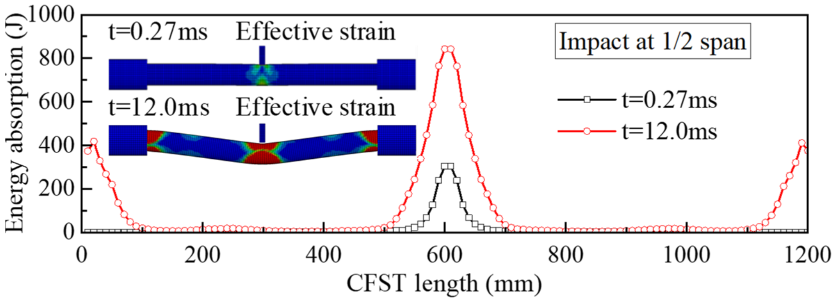
4. Affect of impact position on energy absorption distribution

This investigation reveals the affect of impact position on energy absorption distribution by changing the drop hammer location of the segmented numerical model for the circular CFST member mentioned above. When the impact position is respectively set at 1/2 span, 1/4 span, 1/6 span and 1/8 span, the varying pattern of energy absorption distribution for the circular CFST member is shown in Figure 5, from which the following observations can be made:

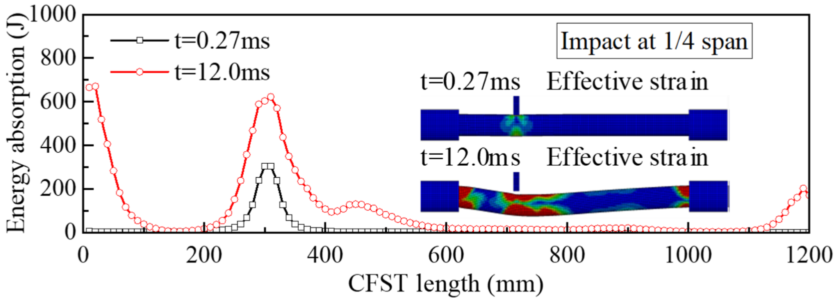
(1) In the local response stage, the energy consumption area of the circular CFST member is only concentrated in impact position, and its distribution and maximum energy consumption do not change significantly with the variation of impact position, which indicates that the impact position has little effect on the energy absorption distribution of the circular CFST member in the local response stage.

(2) In the global response stage, the prime areas of energy consumption for the circular CFST member are distributed at the impact position and the support position. With the impact position approaching one end of the supports, the energy consumption at the impact position and the distal support decrease gradually, while the energy consumption at the proximal support increases gradually, which is consistent with the evolution of the plastic strain and plastic hinge caused by lateral impact.

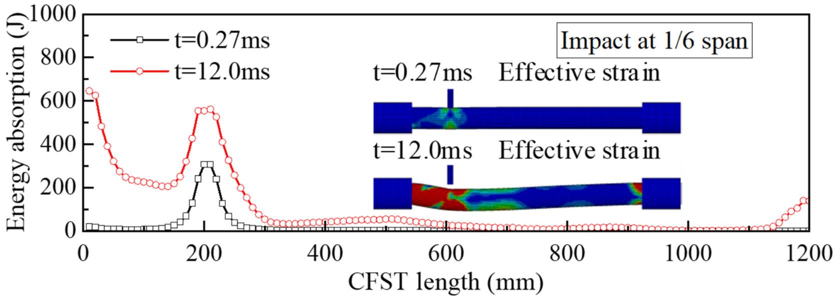
(3) In the whole impact process, there is a relatively long area between the impact position and the supports for the circular CFST member, which is always at a very low energy consumption level. Therefore, the obvious difference of energy absorption distribution along the length of the member should be considered in the impact resistant design and damage reinforcement.



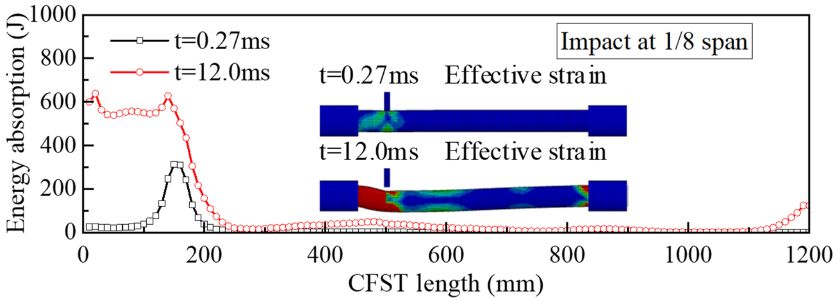
(a) Impact position is at 1/2 span



(b) Impact position is at 1/4 span



(c) Impact position is at 1/6 span



(d) Impact position is at 1/8 span

Figure 5. Affect of impact position on energy absorption distribution.

5. Conclusions

(1) The energy absorption distribution of circular CFST members subjected to lateral impact can be obtained by the segmented numerical model proposed in this investigation, and the results indicate that the prime areas of energy consumption for circular CFST members are distributed at the impact position and the support position, and their areas are 1/6 and 1/12 of the effective length, respectively.

(2) Different from the local response stage, the impact position has a great affect on the energy absorption distribution in global response stage. With the impact position approaching one end of the supports, the energy consumption at the impact position and the distal support decrease gradually, while the energy consumption at the proximal support increases gradually.

(3) A relatively long area between the impact position and the supports exhibits the poor capacity of energy consumption. For the impact resistant design and damage reinforcement, it should be clear that the impact position and the support position are the prime areas of energy consumption, while the other areas of circular CFST members are at a lower energy consumption level.

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