Seismic Performance of Assembled Buckling-Restrained Braced Frame Structure with Replaceable Plasticity-deformation Controllable Steel Hinges

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Abstract: Joints and connections of assembled frame structures are weak in earthquake events, and it is difficult to repair these structures after the earthquake damage. To this end, an assembled buckling-Restrained braced frames structure with replaceable plasticity-deformation controllable steel hinge is presented. Push-over analysis and dynamic time-history analysis are carried out to obtain the seismic behaviour of the new structural such as failure sequence and decreasing ratio for interstory drift angle, and to compare with the traditional assembled frame structure. The results show that the proposed new assembled structure is better than the traditional assembled structure in bearing capacity, lateral resistance, and structural ductility. Also, it can effectively control the nonlinear response of the structure including the displacement of the floor.

1. Introduction

The assembled frame structures are the main structures in construction industrialization. It exhibits these advantages of higher production efficiency, faster construction progress, less construction waste, energy saving and environmental protection. However, the results of the historical seismic damage survey \cite{1} showed that much of the damage to assembled concrete frame structures was due to the serious damage to joints and connections under seismic disasters. In recent years, the relevant scholars put forward a new-type prefabricated loading-unloading beam-column joint \cite{2}, the unbonded post-tensioned pre-stressed beam-to-column dry connections \cite{3}, the assembled concrete frame joints strengthened with core beams \cite{4} and so on to aspire to enhance the seismic performance of assembled joints. The seismic performance of assembled reinforced concrete structures, assembled joints and connections at home and abroad was only close to equivalent to that of the cast-in-place structures. Joints and connections of the assembled frame structures are still the weakest links to resist seismic disasters. In respect of structures, the earthquake resilient structures \cite{5} should be defined as the capability of protecting life safety during a seismic event, restoring its function quickly enough after the earthquake to minimize the influence in serviceability state. The earthquake resilient structures and the systems of replaceable members have become a topic of heat in the structural engineering areas of research and application. Castiglioni, et al. \cite{6} put forward a replaceable connection at the beam ends and made an experimental research on 8 full-scale joint test pieces with this new-type connection. At present, there are few researches on structural systems that the capability of restoring the function for the structures is combined with characteristics of assembled structures.

This paper proposed an assembled buckling-restrained braced frame structure with replaceable
plasticity-deformation controllable steel hinges which were shown in Fig. 1. The new structure was deemed as replaceable members. We could change buckling-restrained braces and energy-dissipation metal flanges connecting plates of the plasticity-dissipation steel hinges in order to restore its function quickly enough after the earthquake damage. Combined with a ten-story assembled reinforced concrete frame structure, Pushover curves, failure sequence, story-drift ratio and seismic mitigation ratio of the innovative structures have been explored by executing static elasto-plastic analysis and dynamic analysis with the application of Midas/Gen.

Figure 1. The assembled buckling-restrained braced frame structure with replaceable plasticity-controllability steel hinges

2. Structure model
A 10-story assembled buckling-restrained braced frame structure with the plasticity-controllability steel hinges was designed. Meanwhile, a conventional assembled frame structure as the comparison of model was designed. The ground floor was 4.5m high and the height of the typical floor was 3.6m. The total height of the overall structure was 36.9m. The seismic fortification intensity was seven degrees (0.15g). The uniform dead load of each floor was 7.0kN/m² and the uniform live load was 2.0kN/m². The FEA model of the innovative assembled frame structure was established with the Midas/gen shown in Fig. 2. The main performance parameters of the buckling-restrained braces were shown in Table 1. The replaceable plasticity-controllability steel hinges of new-type assembled frame structures were installed in the location of the ends of beams. The main performance parameters were shown in Table 2. Selecting a single frame in Axis 2 as an example, the arrangement of buckling-restrained braces and plasticity-controllability steel hinges to new-type assembled frame structures were shown in Fig. 2 and Fig. 3.

Figure 2. The new-type assembled structural model
Figure 3. Schematic diagram of plasticity-controllability steel hinges

Table 1. Main performance parameters of buckling-restrained brace

| Model of BRB | Pre-yield shear stiffness (kN/m) | Yielding displacement (mm) | Yielding load (kN) | Length (mm) |
|--------------|----------------------------------|---------------------------|-------------------|-------------|
| BRB-200      | 166666                           | 1.2                       | 200               | 7500        |
| BRB-160      | 133333                           | 1.2                       | 160               | 7000        |

Table 2. Main performance parameters of plasticity-controllability steel hinges

| Length (mm) | Width (mm) | Height (mm) | Weakening length L3 (mm) | Weakening width b (mm) | Initial stiffness (kN/m) | Yielding rotation (rad) | Post-yield stiffness (kN/m) |
|-------------|------------|-------------|--------------------------|-----------------------|--------------------------|-------------------------|---------------------------|
| 500         | 250        | 600         | 225                      | 50×2                  | 76142                    | 0.003                   | 1280                      |

3. Failure mechanism analysis

The static elasto-plastic analysis methods were conducted to analyze the structural failure mechanism. The structures were loaded in the inverted triangle distribution according to the displacement-control method which meant with regarding 2% structural overall height as the target displacement, we adopted the vibration model load pattern to apply the load.

3.1. Bearing capacity

Observing Fig. 4, the bearing capacity of new-type assembled frame structures was superior to that of conventional frame structures all the time. During the early loading, the buckling-restrained braces of new-type assembled frame structures started to work to enhance the bearing-capacity. During the medium-term loading, the upward trend of the based shear force-top drift curves for conventional assembled frame structures retarded compared with curves of new-type assembled frame structures which still represented uptrend. Once going into post loading, the based shear force-top drift curves of conventional assembled structures were horizontal, while the curves of new-type assembled frame structures still exhibited the rising-trend under the same target displacement.
3.2. Failure sequence analysis

3.2.1. Failure sequence analysis of the conventional fabricated frame structure. The entire structural failure process could be summarized in three parts. When the structural top displacement reached 73.8 mm, the beam ends appeared plastic hinges in Fig. 5(a). When the structural top displacement reached 369.4 mm, the bottom columns appeared plastic hinges with going into the plastic-development stage. With the gradual accumulation of the beam-end damage, there were a large number of plastic hinges emerging at the ends of beams in Fig. 5(b). When the structural top-displacement reached 554.5 millimeters, the third-layer inter-story displacement of structures exceeded limit and occurred structural failure. The distribution of the structural plastic hinges was shown in Fig. 5(c). Observing the ultimate damage-evolution areas of conventional assembled frame structures, the distribution of structural plastic injured parts was rather divergent so as to restore difficultly. So, enhancing the plasticity-controllability performance of structures is still quite necessary.

3.2.2. Failure sequence analysis of the new-type fabricated frame structure. The entire structural failure process could be summarized in four parts. When the structural top displacement reached 36.9 mm, the buckling-restrained braces exhibited the yielding modes. Now the concrete members of the overall structures haven’t appeared obvious damage and plastic hinges were shown in Fig. 6(a). When the structural top displacement reached 110.7 millimeters, the plastic controllable steel hinges began to yield which were shown in Fig. 6(b). When the structural top displacement reached 406.1 mm, the bottom columns appeared the plastic hinges which were shown in Fig. 6(b). The buckling-restrained braces and the plasticity-controllability steel hinges most played an important role of energy-dissipating. While loading to the same end-displacement as conventional assembled concrete frame structures, the integral structural failure hasn’t occurred.

Figure 4. Comparison of loading capacity to two-form structures and their structural failure sequence

Figure 5. Failure sequence of conventional assembled frame structures

(a) Yielding at the beam ends  (b) Yielding at the bottom column  (c) Structure failure

Observing the whole process of the structure failure, the new-type assembled frame structures first appeared the yielding of buckling-restrained braces. The failure sequence of new-type assembled frame structures contented the multilevel seismic design targets that were depicted as strong
column-medium beam-weak brace. By achieving the replacement of buckling-restrained braces and the plasticity-uncontrollability steel hinges, the assembled structures presented the characteristic of the replacing members and restoring its function quickly after the earthquake.

Figure 6. Failure sequence of new-type assembled frame structures

The optimizing effect to structural failure of new-type assembled frame structures was analyzed. The new-type assembled frame structure first emerged the yielding of the buckling-restrained braces, and then its plasticity-uncontrollability steel hinges also began to yield. With the occurrence of the bottom-column yielding, the hinges of the concrete beam ends didn’t emerge and appeared the degradation of the structural bearing-capacity, so as to achieve the multilevel seismic design target that was depicted as strong column-medium beam-weak brace.

4. Dynamic performance analysis

4.1. Select of seismic wave

By selecting three records of the general earthquake ground motion from Pacific Earthquake Engineering Research Center shown in Table 3, the dynamical time-history analysis was executed for both structures.

| Type of ground motion | Seismic station | Moment magnitude | Epicentral distance/m | PGA /m.s^{-2} | PGV /m.s^{-1} | PGD /m | PGV/PGA /s |
|-----------------------|----------------|------------------|-----------------------|---------------|---------------|--------|------------|
| General ground motion | ELcetro        | 6.95             | 34.98                 | 2.75          | 0.31          | 0.09   | 0.11       |
|                       | Taft           | 7.36             | 38.89                 | 1.56          | 0.15          | 0.06   | 0.1        |
|                       | TCU071         | 7.62             | 5.8                   | 5.18          | 0.52          | 0.16   | 0.1        |

4.2. Inter-story drift ratio and damping ratio

Table 4. Damping rate of structural inter-story drift ratio under the rare earthquake

| Story | Conventional structural inter-story drift ratio | New-type structural inter-story drift ratio | Damping ratio of inter-story drift ratio |
|-------|-------------------------------------------------|---------------------------------------------|----------------------------------------|
|       | Elcetro Taft TCU071 Average                     | Elcetro Taft TCU071 Average                 | Elcetro Taft TCU071 Average             |
| 1     | 0.0056 0.0038 0.0036 0.0043 0.0035 0.0023 0.0026 0.0085 | 37.6% 38.1% 26.4% 34.0% | |
| 2     | 0.0092 0.0038 0.0058 0.0069 0.0055 0.0035 0.0040 0.0130 | 40.4% 39.0% 31.2% 36.8% | |
| 3     | 0.0095 0.0054 0.0064 0.0071 0.0056 0.0041 0.0041 0.0138 | 41.8% 23.9% 35.1% 33.6% | |
| 4     | 0.0093 0.0051 0.0062 0.0069 0.0060 0.0044 0.0041 0.0145 | 35.4% 14.1% 33.8% 27.8% | |
| 5     | 0.0081 0.0057 0.0069 0.0069 0.0057 0.0042 0.0037 0.0135 | 29.7% 27.4% 46.5% 34.5% | |
| 6     | 0.0065 0.0058 0.0067 0.0064 0.0045 0.0036 0.0032 0.0113 | 31.2% 38.3% 53.1% 40.9% | |
| 7     | 0.0048 0.0050 0.0056 0.0051 0.0033 0.0029 0.0026 0.0088 | 30.8% 41.5% 54.2% 42.1% | |
| 8     | 0.0039 0.0040 0.0042 0.0041 0.0025 0.0023 0.0020 0.0067 | 35.4% 43.1% 54.0% 44.2% | |
| 9     | 0.0031 0.0031 0.0031 0.0031 0.0017 0.0015 0.0013 0.0045 | 45.6% 49.6% 59.4% 51.5% | |
| 10    | 0.0020 0.0019 0.0019 0.0020 0.0009 0.0008 0.0007 0.0024 | 55.3% 57.3% 64.8% 59.1% | |
From Table 4, the damping effect of the maximum elasto-plastic Inter-story drift ratio to the new-type prefabricated structures under the rare earthquake was rather obvious, that meant the average damping ratio was between 27.8% and 59.1%, especially emerging the decreasing of Inter-story drift ratio and damping ratio between Floor 3 and Floor 4. The decreasing percentage was 33.6% and 27.8%. Floor 3 and Floor 4 was the structural weak storey. The new-type structures could control the structural nonlinear response efficiently.

4.3. The distribution of plastic hinges
The beam-ends of conventional assembled structures occurred a large number of plastic hinges focusing at the bottom-ground columns. There were relatively few plastic hinges of the plasticity-controllability steel hinges in the mid-span of the buckling-restrained braces. Because of the improvement of the structural lateral stiffness attributing to the buckling-restrained braces, it indicated that the plasticity-controllability steel hinges of new-type assembled frame structures achieved the moving of plastic hinges at the beam ends. After the earthquake, the damaged components can be replaced rapidly. Restoring to the immediate occupancy of structures achieved the requirements of replaceable and recoverable functions for the assembled structures.

![Figure 7. Distribution of structural plastic steel hinges](image)

5. Conclusions
Some conclusions have been obtained.

1) The load-bearing capacity of the reinforced concrete buckling-restrained frame structures with the plasticity-controllability steel hinges was superior to that of conventional assembled frame structures.

2) The reinforced concrete buckling-restrained frame structures with the plasticity-controllability steel hinges under the rare earthquake could efficiently control structural nonlinear.

3) After the seismic damage, the damaged buckling-restrained braced frames and the plasticity-controllability steel hinges could be replaced rapidly. It achieved the requirements of the replaceable and recoverable functions for the assembled structures.

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