Effect of Inertia Force During High-Speed Reversed Cyclic Loading

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Introduction

During quasi-static tests of beam-column joints, cyclic displacements are applied slowly so that the actuator has enough time to perfectly execute the loading direction reversal. In contrast, during high-speed tests, an actuator has to change loading direction rapidly to exactly follow the intended displacement history. However, most actuators cannot maintain the intended loading speed and simultaneously follow a sharp peak at the reversal point. Consequently, the displacement history followed by an actuator shows a smooth transition around the peak of each cycle. Inside this transition phase, the velocity gradually decreases and a large negative acceleration exists, which induces a significant inertia force that is included in the load cell reading. If the high-speed displacement cycles are applied at the column-top, the inertia force must be accurately determined to know the correct value of storey-shear, which is the most important parameter for result interpretation. On the other hand, if the displacement cycles are applied at the beam-tips and the column-top is held stationary, the load cell reading at the column-top is free of inertia effect and gives the exact value of storey-shear. Nevertheless, the beam-tip load cell readings are influenced by inertia force. This mechanism is discussed here based on the results of a high-speed cyclic loading test of a lightly reinforced beam-column subassembly.

Test details

The beam-column joint specimen consists of a 3.7 m high column and a 5.4 m long beam. The 300×550 mm beam is reinforced with eight 32 mm diameter bars, six of them at the top and two at the bottom with a clear concrete cover of 20 mm. Similarly, the 400×400 mm column is reinforced with eight 25 mm diameter bars arranged symmetrically with clear concrete cover of 35 mm. The stirrups in the beam comprise of four legs of 10 mm diameter bars spaced at 200 mm, and the ties in the column have three legs of 10 mm diameter bars with 150 mm spacing. The specimen has no vertical or lateral hoops inside the joint core. Moreover, the longitudinal reinforcing bars in the column are overlapped just above the joint, and the beam reinforcing bars at the bottom are discontinuous with the overlapping located close to the joint core with less than 100 mm penetration into the joint core. The lightly reinforced specimen is of strong-beam weak-column type. The compressive strength of the concrete is 31.7 MPa. The yield strengths of 32 mm, 25 mm and 10 mm diameter bars are 538 MPa, 537.6 MPa and 363.7 MPa, respectively. Similarly, the ultimate tensile strengths are measured to be 677.3 MPa, 675.3 MPa and 571.5 Mpa, respectively.

As shown in Figure 1, the end plates at the beam-tip are pinned to vertical actuators. The column-top is supported with a universal-pin joint, and the bottom of the column is clamped to the rig against translation as well as rotation. Measuring the distance between the centrelines of the supports at two extremes, the effective height of the column is 3.2 m and the effective length of the beam is 6.0 m. Axial compression (10-15% of the axial capacity) is applied through two prestressing tendons connected to a steel H beam at the top of the column. Equal and opposite high-speed displacement cycles are applied to the two beam-tips at a constant loading frequency of 2 Hz; i.e. two cycles per second. The amplitude of the cyclic displacement is increased gradually from 0.25% radian to 2% radian inter-storey drift angle with a 0.25% radian increment at each step. After reaching 2% radian inter-storey drift angle, the increment is changed to 0.5% radian until reaching 4% drift angle. The first displacement cycle corresponding to 0.25% radian inter-storey drift angle is applied once only, and each cycle after that is repeated three times to observe any strength deterioration due to load repetition. LVDT transducers are used to measure the displacements at the beam-tips and also the support movements at the column-ends. The vertical forces at the beam-tips and the horizontal reaction at the top of the column are measured with load cells.

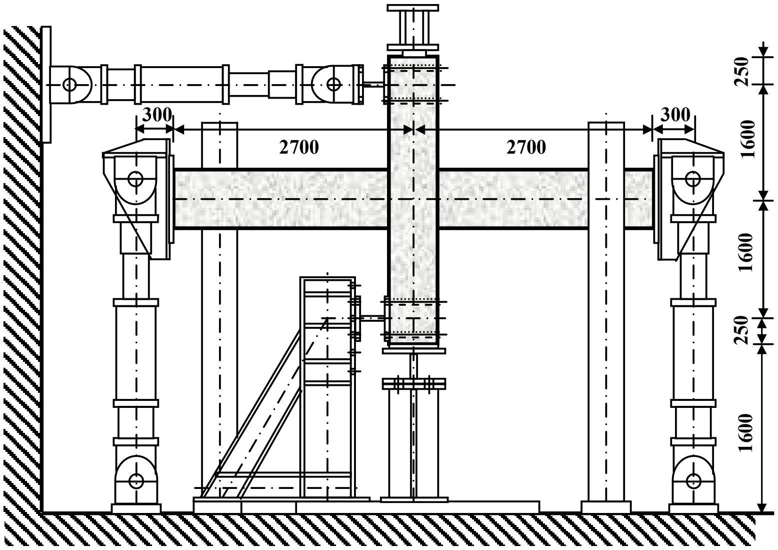

Figure 1. Test set-up

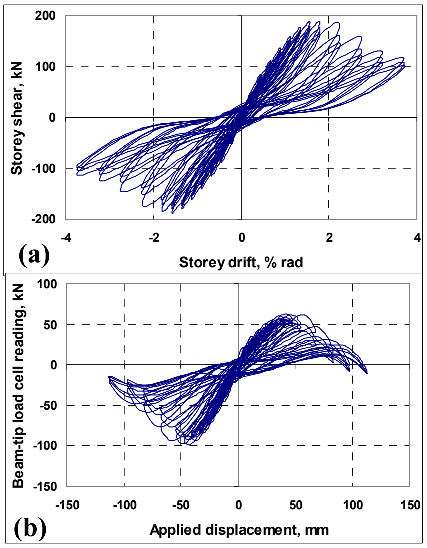

Figure 2. Test results

Results and discussions

The storey-shear versus storey-drift relationship for the specimen is depicted in Figure 2(a). Here, the storey-shear is the load cell reading at the column-top, and the inter-storey drift angle is the average rotation of the line joining the beam-tips from the original beam axis. Maximum storey-shear of the specimen is 188.4 kN, which is reached at the peak of the first displacement cycle intended to induce 1.75% radian inter-storey drift angle, though the measured drift angle is slightly less. In the later displacement cycles, considerable post-peak softening of the storey-shear is observed, and the specimen exhibits a significant pinching behaviour. The difference between storey-shears recorded in the first and the third cycle peaks is significant in the post-peak region. As the specimen is symmetric, and equal and opposite displacements are applied at the two beam-tips, the load-displacement relationships at both loading points are almost identical. The load versus displacement curve at one of the actuators is plotted in Figure 2(b). The maximum load corresponding to the two opposite directions are not equal because of the different amounts of reinforcement at the top and bottom of the beam. Interestingly, the load cell reading is found to suddenly unload at the positive and negative peaks of each displacement cycle. This behaviour becomes more prominent during larger displacement cycles.

This behaviour is due primarily to the development of large acceleration in the direction opposite to that of the displacement being applied. As shown in Figure 3, the displacement reversal at the positive peak of each cycle induces a sudden change of velocity from positive to negative value. Correspondingly, a negative spike will be formed in the acceleration history. Nevertheless, due to the mechanical limitation, the actuators cannot switch sharply their movement from/to outward to/from inward direction, and needs some time in doing so. Consequently, there appears a smooth transition phase around the peaks of each displacement cycle. The maximum displacement that could be applied is also slightly less than the intended magnitude. As the transition phase is very short, the induced negative acceleration becomes large; thus generating a significant inertia force.

As the column-top is restrained against lateral movement, inertia force cannot be generated there. Hence, the load cell reading at the column-top correctly represents the storey-shear.

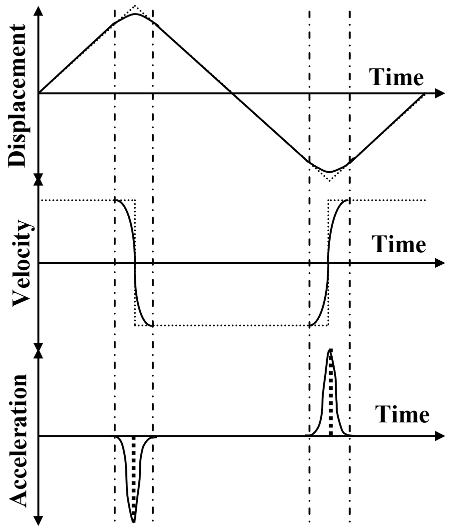

Figure 3. Negative acceleration during high-speed displacement reversal

Although the mechanism can be explained as above, it is difficult to separate the exact contribution of inertia force from the load cell reading. To compute the inertia force, the acceleration needs to be multiplied by the exact value of participating mass, which induces a fair degree of uncertainty in the computation. The output displacement history obtained from the LVDT attached in the actuator is shown in Figure 4(a). As mentioned earlier, a smooth transition exists around the peak. The acceleration history shown in Figure 4(b) derived from the output displacement history clearly identifies spikes at the peak of each cycle in the direction opposite to the displacement being applied. The participating mass at each beam-tip should comprise of the mass of the connecting plate and also an equivalent mass for the beam, which is difficult to estimate exactly. Few trials assuming different values in a logical range (600-1200 kg) were performed, and the corrected force-displacement curves assuming the participating mass equal to 800 kg is shown in Figure 4(c). The result shows that the normal shape of the static force-displacement curves could be restored after deducting the inertia force from the load cell readings.

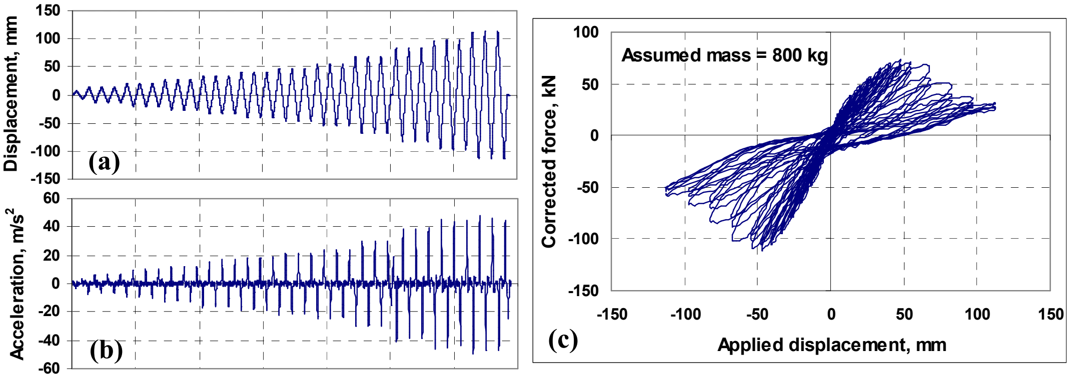

Figure 4. Separation of inertia force from the load cell reading

Conclusions

In this paper, high-speed cyclic loading test on a lightly reinforced beam-column sub-assembly is discussed, and the effect of inertia on the experimental result is highlighted. The results manifested that the load cell reading at the high-speed loading actuator includes the contribution of inertia force, which exists specially around the peaks of the displacement cycles. The direction of the induced inertia force is opposite to that of the displacement being applied, and its magnitude increases during larger displacement cycles. As the estimation of participating mass cannot be exact, it is recommended to directly record correct storey-shear instead of separating inertia force from the contaminated readings. For this, high-speed cyclic displacement should be applied at the beam-tips and storey-shear should be directly measured from a load cell at the column-top support rather than deriving it from the beam-tips load cell readings.