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BATTENED BUILT-UP BEAM-COLUMNS UNDER CYCLIC LOADS

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SUMMARY

The battened double-channel columns designed as per current practice may behave satisfactorily in axial compressive loading, but during seismic overloads, they may not be able to withstand the lateral load required to reach full plastic moment carrying capacity of section. The tests showed that under constant axial load and varying cyclic lateral loads, specimens with conventional design configuration failed to reach its full plastic moment capacity of section prior to failure due to instability. The degradation of flexural strength and stiffness of the member started from the onset of local buckling of flanges and webs of channel section. The design of battened beam-column was modified in two stages by changing the configuration of batten in the plastic hinge region, i.e., a) reducing the spacing of battens in the end panel by half, and b) "boxing" the end panel section by a wider batten. The modified designed specimens showed excellent performance in terms of flexural strength and stiffness, moment rotation response, ductility and energy dissipation capacity as compared to specimen designed as per current code specifications. The specimens having "boxing" configuration reached its full plastic moment carrying capacity.

INTRODUCTION

A built-up column is a kind of compression member consisting of two identical parallel elements slightly separated and connected to each other at only a few places along their length by means of connector like lacings, battens or perforated plates. These members are frequently used as light compression members, such as struts in truss moment frames and as columns of light steel structures. Double-channel sections are often used as built-up columns, which are connected to each other at few places by means of battens. Typically the battens are designed to carry the bending moments and shears arising from transverse shear force of 2.5 percent of the total axial force on the whole compression member at any point in the length of the member, divided equally between parallel planes of battens and the battens are placed at a uniform spacing throughout the length of member. Due to wind or earthquake forces, the built-up columns have to

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carry lateral load in addition to primary axial compressive load, and hence, these members behave as beam-columns.

Little research has been done on the behaviour of battened built-up columns subjected to lateral loading. However, the earlier studies by Bleich [1] and Timoshenko [2] on behavior of built-up column revealed that the member deformations due to shear have an adverse effects on the axial buckling strength of built-up members. The reduction in axial buckling strength due to the shear deflection is therefore much greater than in the case of columns of solid cross-section and hence, depends upon the dimensions and the structural connections of the connectors. Uang [3] showed that in addition to the shearing effect, the compressive strength can be reduced by compound buckling, where in the localized buckling of flange components between the battens interacts with the global buckling mode. The effect of stitch spacing and local buckling on the axial buckling strength under monotonic loading has been studied by many investigators. Goel [4] showed that the smaller width-thickness ratio reduce the severity of local buckling, leading to an increase in ductility and energy dissipation capacity of double-angle braces.

During seismic overloads, the built-up columns are subjected to excessive compressive strain due to lateral loads in addition to that of due to axial compressive load. This study examines the effect of battens and their connections of battened double-channel beam-columns. The objective was to develop a design of ductile built-up beam-column, which can reach full plastic moment carrying capacity of the section without instability. The study was based on tests of five battened double-channel members being subjected to axial compressive loads and reversed cyclic lateral load (Figure 1). The reversed cyclic loads were established so that the battened double-channel members experience substantial inelastic deformations in tension and in compression in presence of axial compressive loads, similar to those expected during earthquakes. Base plates were used at the ends to connect the members to the test set up and the gusset plates were used at the fixed end to connect the members to the base plate. The end connections and the connection of battens with channels were done by means of welding.

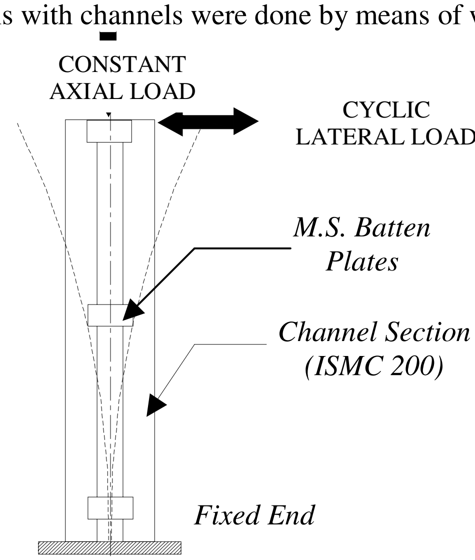


Figure 1: Battened Double-Channel Member Subjected to Axial Compressive Load and Cyclic Lateral Load

TEST SPECIMENS

Tests were performed on five full scale models of double-channel beam-columns. Indian standard rolled channel sections (ISMC 200) were used as main components and welded mild steel plates are used as battens for all specimens. The dimensions and properties of cross-section of ISMC 200 are given in Table 1. The length of member was chosen corresponds to the point of inflection that would occur in the event of an earthquake; that is, at the mid-story height of column. The specimens were fixed at an end and free at other. The end connections were made of welded gusset which resulted in ductile behaviour. In the present study, three different designs of battened members are used. The details of batten configuration in all test specimens are given in Table 2.

***Table 1*: Dimension and properties cross-section of ISMC 200**

a (mm^2)	*h (mm)*	*b_f (mm)*	*t_f (mm)*	*t_w (mm)*	*I_{xx} (x cm^4)*	*I_{yy} (x cm^4)*
2821	200	75	11.4	6.1	1819.3	140.4

***Table 2*: Geometric properties of Test Specimens**

<table>
<tr><th>Specimen</th><th>Length (mm)</th><th>Batten Configuration</th><th>Panel length</th><th>Comments</th></tr>
<tr><td>DC1C</td><td rowspan="5">1200</td><td>140x120x10m (6 no.)</td><td>370 mm (2 no.)</td><td>Conventional Design</td></tr>
<tr><td>DC1M</td><td rowspan="2">140x120x10mm (8 no.)</td><td rowspan="2">370 mm (1 no.)
125 mm (2 no.)</td><td rowspan="2">Half batten spacing near fixed end</td></tr>
<tr><td>DC2M</td></tr>
<tr><td>DC1MB</td><td rowspan="2">140x120x10mm (4 no.)
140x365x10mm (2 no.)</td><td rowspan="2">370 mm (1 no.)
125 mm (2 no.)</td><td rowspan="2">“Boxing” configuration near fixed end</td></tr>
<tr><td>DC2MB</td></tr>
</table>

Conventional Battened Built-up member

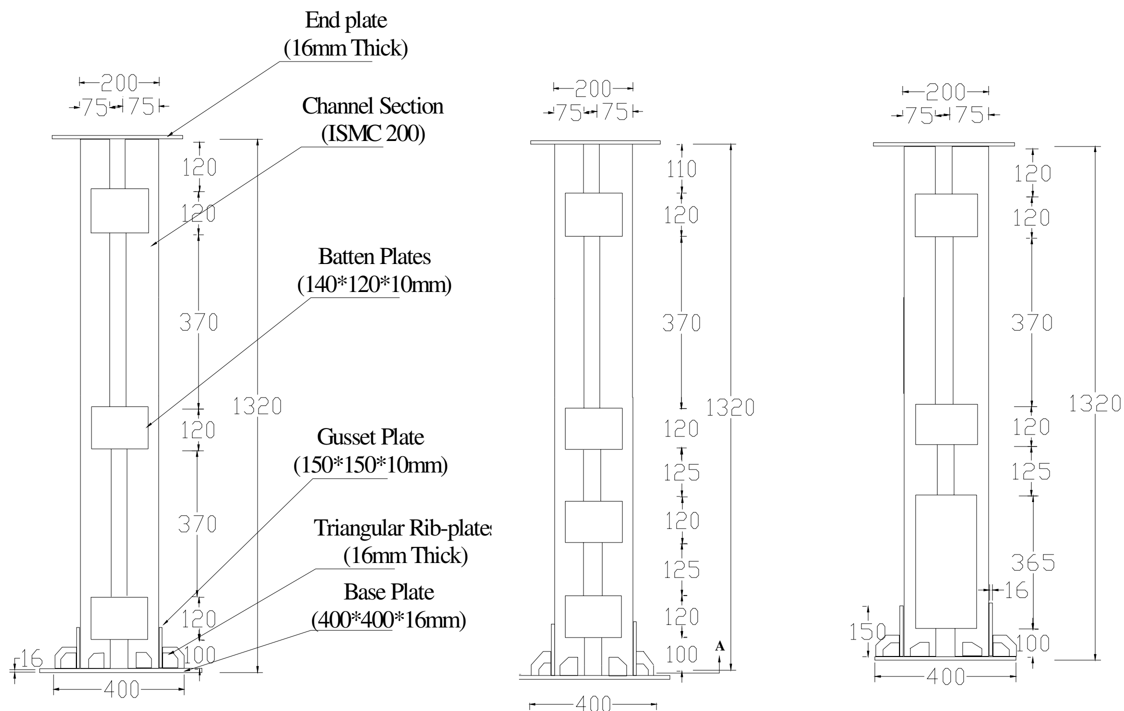
This specimen consists of two channel (ISMC200) sections as main components with uniform spacing battens throughout its length. The spacing requirement of battens is as per Indian Standards IS: 800 [5] which states that “the spacing of battens center-to-center of end fastenings shall be such that the slenderness ratio of the lesser main components over that distance shall not greater than 50 or greater than 0.7 times the slenderness ratio of the member as a whole about the axis parallel to the battens.” This stipulation led to a uniform batten spacing of 490mm center-to-center for the specimen DC1C. This consideration is applicable to the compression members carrying axial load only and serve its intended All battens were of same configuration. This specimen was designated was DC1C in which DC stands for double-channel battened built-up member, 1 stands for specimen number in the same category, and C stands for conventional design. One specimen of this conventional design of battened built-up member was tested in the present study. The details of double-channels battened member with batten configuration are shown in Figure 2(a).

Modified Battened Double-Channels Built-up Members

Tests showed that the components of conventionally designed battened built-up member exhibited severe local buckling and buckled laterally closing the gap between the main components and thus, the full plastic moment carrying capacity of the section could not be reached. Hence, an attempt was made to examine the effect of strengthening the flanges in the expected plastic hinge region of battened member so as to reduce the gap closing and instability. The design of battened double-channel built-up member was modified by reducing the spacing of battens in the expected plastic hinge region. An additional batten of same configuration was placed at the mid-way of the first panel nearer to fixed end in both side of built-up member so that the batten spacing in this panel was reduced by half. This specimen was designated was DC1M in which DC stands for double-channel battened member, 1 stands for specimen number in the same category, and M stands for modified design. Two specimens of this design were tested in the present study. The details of these specimens are shown in Figure 2 (b).

Battened Double-Channels Built-up Members with ‘Boxing’ Configuration

Tests showed that the specimens having modified design of battens in the end panel behaved better then conventionally designed specimen. However, the specimens could not reach their full plastic moment carrying capacity without instability. Hence, the design of double-channels battened built-up member was further modified by changing the batten configuration in the expected plastic hinge region. A very wide batten was used in place of two end battens nearer to fixed end in the modified designed test specimens so that a "boxing" configuration was achieved. The thickness and depth of wide batten plate was kept same as other battens. This specimen was designated as DC1MB in which DC stands for double-channel battened member, 1 stands for specimen number in the same category, and MB stands for modified design with "boxing" configuration. Two specimens of this category were tested. The details of batten configuration of these specimens are shown in Figure 2 (c).



a) Specimen DC1C *b) Specimens DC1M & DC2M* *c) Specimens DC1MB & DC2MB*

***Figure 2*: Details of Test Specimens**

TEST SETUP & LOADING HISTORY

The test setup shown in Figure 3 consisted up a reaction frame, two double-acting servo-hydraulic actuators, and a reaction block. Two servo-hydraulic (SH) actuators, namely Model 244.31A (force rating: ±250kN; stroke length: ±150mm) and Model 244.45T (force rating: ±500kN; stroke length: ±150mm) were used to apply loads to the test specimens. The 500kN and 250kN actuators were used to apply constant axial compressive force and cyclic lateral load to the test specimens, respectively. A steel reaction frame was constructed to support the 250kN actuator providing lateral load to the specimen in vertical plane. The frame consisted of four steel columns, which were firmly tightened to reinforced concrete strong floor by means of bolts. The test specimens were laid horizontally having its fixed end attached firmly to the reaction block attached to the strong floor and the other end, which was considered as free end, was connected to the 500kN actuator. The 250kN actuator was attached to the free end of test specimens.

Instrumentation included four linear variable differential transducers (LVDTs) for lateral displacement measurement at free end and three intermediate points spaced at one-fourth of length of specimen, two load cells for measurement of axial compressive load and cyclic lateral load attached to the actuators, and

CEA-strain gauges (manufactured by Measurement Groups, USA) for measurement of strain at critical points such as mid points of webs in the vicinity of end connection, mid-points of flanges and battens.

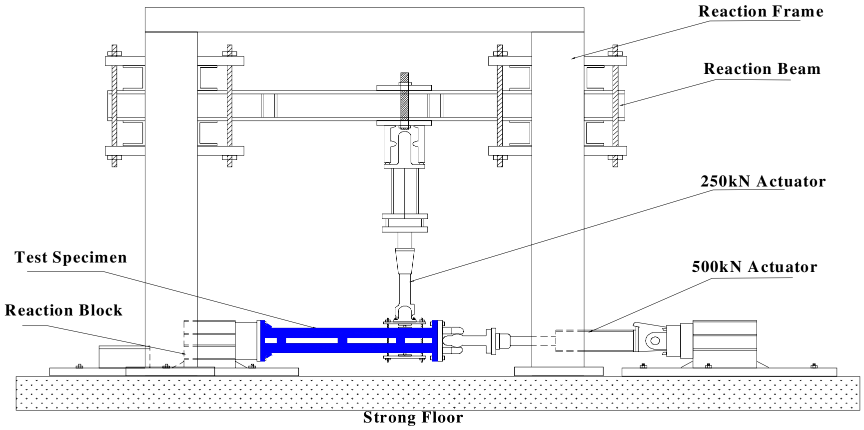


***Figure 3*: Details of Test Specimens**

Displacement Loading History

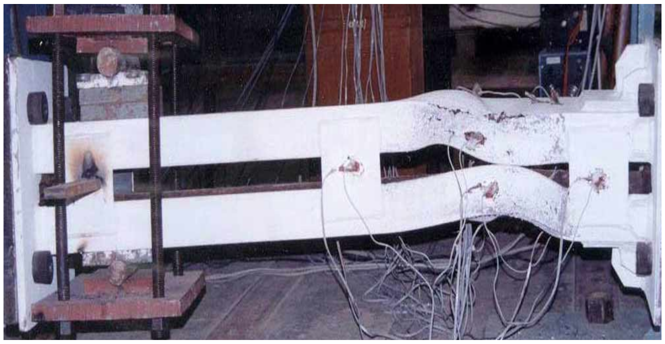
A simple multiple-step loading history based on ATC-24 [6] guidelines was considered. According to this, if the purpose of the test program is to assess the seismic performance of a component, then a multiple-step loading history which consists of symmetric cycles of increasing amplitude in predetermined steps is adequate. The push displacement applied by actuator was taken as positive and the pull displacement was taken as negative. The displacement cycle levels adopted for the specimens are ±3, ±6, ±9, ±12, ±15, ±18, ±21, ±30, ±40 and ±60mm. The displacement loading cycle at each of the excursion level is repeated three times to get the repetitive behavior of the specimens at the particular level. The loading cycles are suggested linear up to onset of yielding and then increased with 1.5, 2, 3, etc., times of yield displacements. The cyclic displacement loading history was applied after the specimens were loaded with constant axial compressive force. This procedure was adopted to simulate the actual field condition where the battened double-channel built-up column carrying axial compressive load subjected to lateral force due to earthquake loading.

OVERALL BEHAVIOUR OF SPECIMENS

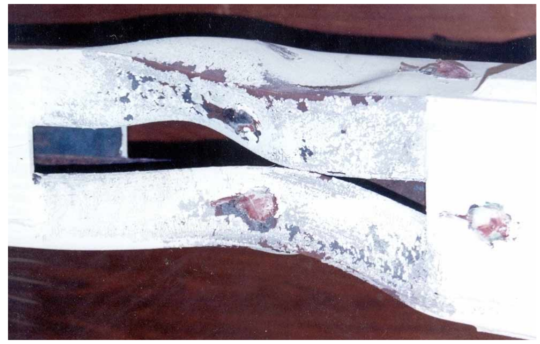
The test specimens were subjected to constant axial load of half of allowable axial load and gradually increasing reversed cyclic deformation history. The behavior of specimens in terms of local buckling, lateral buckling, and full plastic moment carrying capacity is discussed in the following section:

Specimen DC1C

The specimen showed elastic behaviour up to ±15mm cyclic excursion level and no yielding was observed anywhere in the specimen. First yielding was observed during cyclic displacement of ±18mm excursion level in the webs of specimen. With increase of excursion level, the webs in the end panel started to buckle in form of bulging inward. This induced the unsupported flanges of specimen in the end panel to buckle sideways and thus closing the gap between the components of specimen was observed as shown in Figure 4. The local buckling of components induced the lateral buckling of specimen. This instability of components reduced the lateral load carrying capacity and the specimen failed to reach its full plastic moment carrying capacity. The average lateral load carried by the specimen was found to be 68.5kN which was about 68% of the load required to produce full plastic moment carrying capacity of the section.



a) Failure of Specimen DC1C



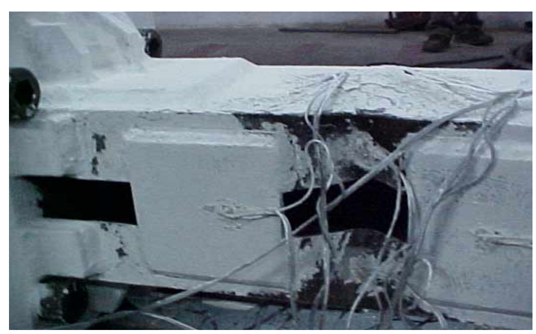
b) State of webs and flanges in the failure region

Figure 4: **Failure of Specimen DC1C**

Specimen DC1M

The elastic behavior observed in the specimen was up to ±15mm excursion level and first yielding was observed in ±18mm cyclic excursion level which was same as observed in specimen DC1C. However, the load carried by the specimen was observed higher than that of the specimen DC1C. The local buckling of webs and flanges was observed after yielding of specimen. The web buckling was observed in the form of outward bulging of webs just after end connection region and the flange buckling in the form of inward bulging was observed in the panel between end batten and additional batten. The web and flange local buckling was observed during ±30mm cyclic excursion level. The instability of specimen was concentrated in the localized area in the end panel and no instability was observed in rest part of specimen. The local buckling in the main components induced the lateral buckling of the specimen which was observed during ±40mm. The gap closing of components of specimen was not observed up to failure of specimen. Figure 5 shows the failure of Specimen DC1M and state of webs and flanges of specimen in the plastic hinge region. The maximum lateral loads carried by the specimen in both directions were +76.1kN and -103.7kN and, thus the average load were found to be 89.9kN. These peak loads were observed during ±30mm cyclic excursion level. The specimen was able to reach about 90% of its full plastic moment carrying capacity.

a) Failure of Specimen DC1M



b) State of web and flange in the plastic hinge region of Specimen DC1M

Figure 5: **Failure of Specimen DC1M**

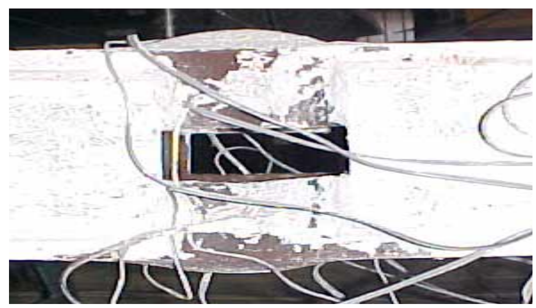
Specimen DC2M

This specimen was a repetition of test specimen having reduced batten spacing in the end panel. The specimen behaved elastically up to ±15mm cyclic excursion level and no yielding was observed any where in the specimen. The localized yielding was observed in the web of specimen during ±18mm cyclic excursion level. The web local buckling and flange local buckling was observed in ±30mm cyclic excursion level. Also, no gap closing of components was observed in the specimen during failure. The mode of failure of specimen was found to be same as that of Specimen DC1M. The maximum lateral load carried by the specimen was 79.4kN. The failure of specimen was observed in the first cycle of ±40mm cyclic excursion level. The early failure of specimen was due to failure of welding in the fixed end connection.

Specimen DC1MB

The elastic behavior of specimen without any yielding was observed up to ±15mm cyclic excursion level and afterwards yielding was observed in the web of specimen. The load carried by the specimen in each cycle was found to be higher than other specimens. The "boxed" region did not show instability, however, the instability of webs and flanges was observed in the panel beyond the "boxed" region. The outward bulging of both webs was observed which was associated with inward bulging of flanges in ±30mm cyclic excursion level. The maximum cyclic excursion level carried out before failure was ±50mm. The specimen buckled laterally in the panel just after "boxed" region. The maximum lateral loads carried by the specimen in both positive and negative direction were found to be 101.7kN and 83.1kN, respectively. The average lateral load carried by the specimen was 92.4kN. The maximum loads were observed during ±40mm cyclic excursion level and specimen started to buckle laterally. Figure 6 shows the overall failure of specimen and state of components during failure.

a) Failure of Specimen DC1MB



b) State of web and flange in the plastic hinge region of Specimen DC1MB

Figure 6: **Failure of Specimen DC1MB**

Specimen DC2MB

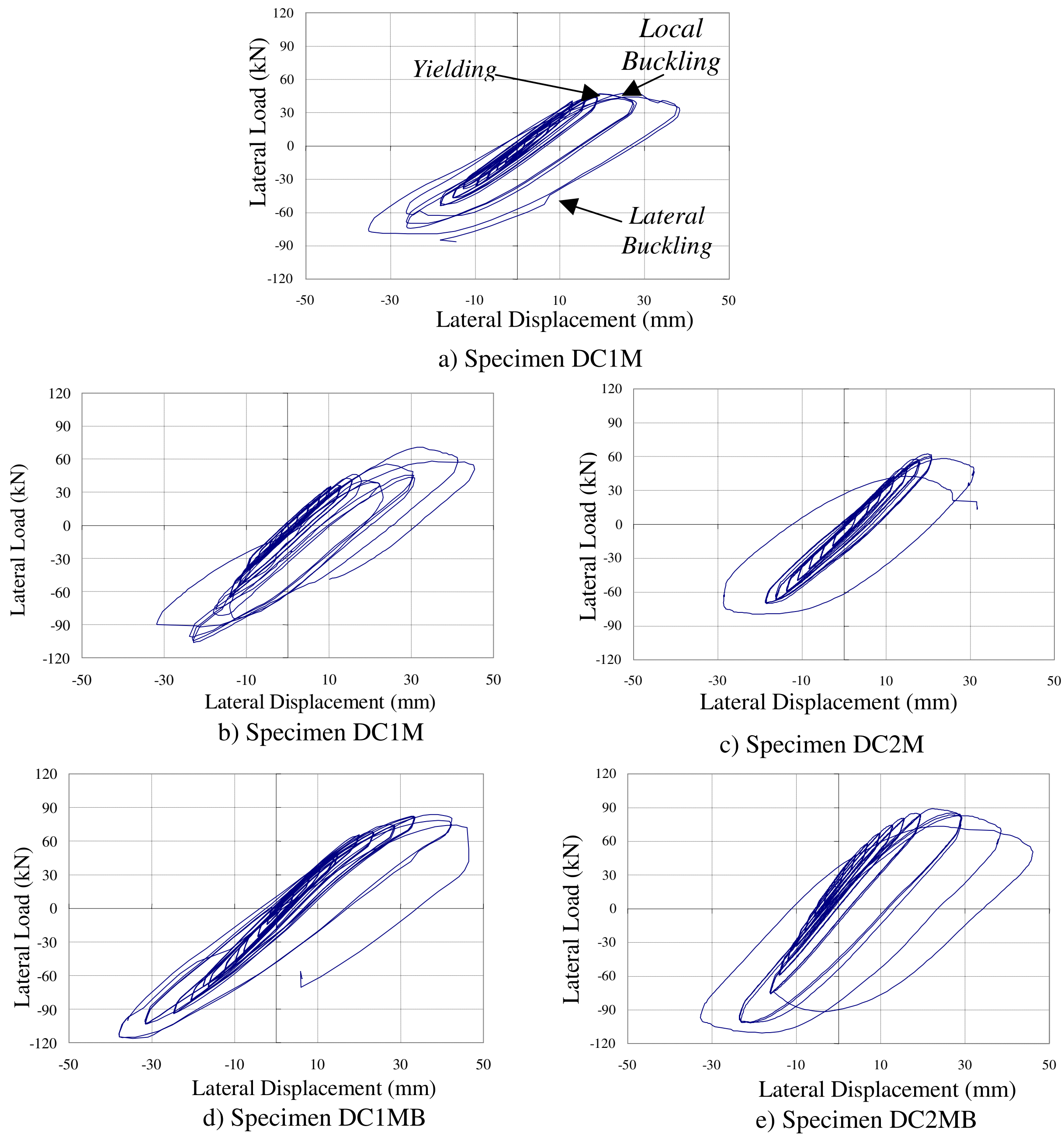
This specimen is the repetition of battened column having "boxing" configuration in the expected plastic hinge region. The specimen behaved similar to the Specimen DC1MB. The yielding of specimen was observed in ±18mm cyclic excursion level. The outward bulging of both webs was observed which was associated with inward bulging of flanges in ±30mm cyclic excursion level. However, the maximum cyclic excursion level reached by the specimen was ±40mm. The maximum lateral loads carried by the specimen in both positive and negative direction were found to be 82.8kN and 110.4kN respectively. The average lateral load carried by the specimen was 96.6kN. The maximum loads were observed during ±40mm cyclic excursion level and specimen started to buckle laterally in the last cycle of excursion level. The plastic hinge was observed in the first panel just after "boxed" region.

TEST RESULTS

This section presents the test results that show how the batten spacing and configuration in the plastic hinge region influence the seismic performance of specimens. The overall slenderness ratio of the specimens was kept constant because the modification was done on the battened column having same size and cross-section.

Lateral Force-Lateral Displacement Response

The lateral reaction force exerted by the specimen due to application of lateral cyclic displacement was plotted with corresponding cyclic displacement. Figure 7 (a) shows elastic response of Specimen DC1C up to ±15mm cyclic excursion level. The loading and unloading curves in both direction of loading were found to be almost linear. The inelastic response was observed with widening of lateral force-lateral displacement curve. With increase of excursion level, the curve widened further. During ±30mm excursion level, the local buckling of the webs and flanges was observed. The specimen was buckled laterally during ±40mm cyclic excursion level.



a) Specimen DC1M

b) Specimen DC1M

c) Specimen DC2M

d) Specimen DC1MB

e) Specimen DC2MB

***Figure 7*: Lateral Force-Lateral Displacement Response of Specimen DC1C**

Figure 7 (b) shows lateral load-lateral displacement curves of Specimen DC1M. The linear portion of curve, which corresponds to the elastic response, was observed up to ±15mm cyclic excursion level. The same was observed in case of Specimen DC1C. During ±18mm cyclic displacement, initial inelastic response was observed in the specimen and the curve for third cycle of excursion level widened. During ±30mm excursion level, the local buckling of the webs and flanges was observed and the lateral force-displacement curve. The lateral buckling of the specimen was observed during second cycle of ±40mm cyclic excursion level.

Figure 7 (c) shows lateral load-lateral displacement curves of Specimen DC2M. The elastic behavior was observed up to ±15mm cyclic excursion level. During ±18mm cyclic displacement, initial inelastic response was observed in the specimen. During ±30mm excursion level, the local buckling of the webs and flanges was observed and the specimen failed during ±30mm excursion level in lateral buckling.

Lateral load-lateral displacement curve of Specimen DC1MB is shown in Figure 7 (d). The specimen was nearly elastic up to ±18mm cyclic excursion level. During ±21mm cyclic displacement, the widening of curve, which marked the inelastic response of specimen, was observed. The yielding was observed in the webs adjacent to the "boxed" region. During ±30mm excursion level, the local buckling of the webs in the form of outward bulging was observed which caused the lateral fore-displacement curve to widen further. During ±40mm cyclic excursion level, severe local buckling of flange of specimen was observed which led to the overall lateral buckling and considerable decrease in the strength and stiffness.

Figure 7 (e) shows lateral force- lateral displacement curve of Specimen DC2MB. The same behavior as observed in Specimen DC1MB was observed in this specimen also. However, hysteretic loops observed in the specimen were wider than the previous specimen. The loops were symmetric in both directions. The yielding was started in ±20mm cyclic excursion level which was observed in the webs of specimen next to the "boxed" region. During ±30mm excursion level, the hysteretic loop widened at a particular load level which marked the local bulging of webs. During first cycle of ±40mm excursion level, the local buckling of the flange was observed and in the second cycle the specimen failed in global lateral buckling.

Lateral Strength

Figure 8 shows the peak lateral load-displacement response of test specimens. The curve is obtained from average peak loads of three cycles of an excursion level with corresponding the cyclic displacement. The lateral loads carried by the Specimen DC1C at each level of cyclic loading are smaller than that of other specimens. Specimen DC1M and DC2M shows the medium lateral strength which lies between that for Specimen DC2MB and Specimen DC1C. Specimen DC1MB and DC2MB have the lateral strength capable of reaching full plastic moment carrying capacity of the section. Specimen DC2M shows the lateral strength up to ±30mm cycle because the specimen failed during first cycle of ±30mm cyclic excursion level.

Further, it can be seen that during initial cycles of displacement loading history, the behavior of the specimens was not much affected by changing the batten configuration on the expected plastic hinge region. In large cyclic excursion level, the behavior is greatly influenced by batten configuration. The reduction of batten spacing by half in the expected plastic hinge region of battened column increased its lateral strength, but could not help it achieve its full moment carrying capacity. The instability of specimen may occur in the components in the first panel of battens. The specimen having "boxed" configuration using a very wide plate in the expected plastic hinge region improved the lateral strength and reached its full plastic moment carrying capacity.

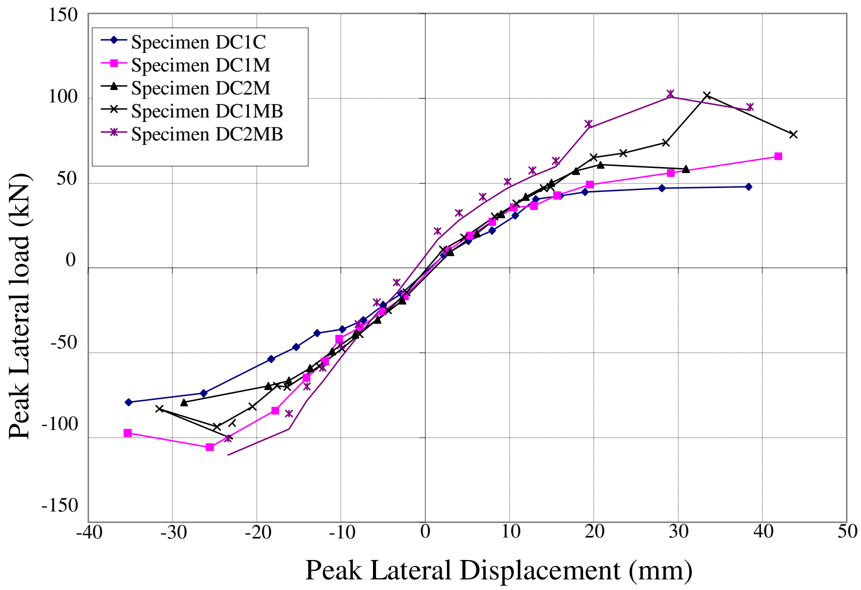


Figure 8: **Peak Lateral loads and Displacements of all Specimens**

Lateral Stiffness

Figure 9 shows the lateral stiffness of specimens at different cyclic excursion level. The stiffness of specimens was calculated from the average peak loads in both directions of cyclic loading in each excursion level to the corresponding cyclic displacements. The initial stiffness of specimen DC1C was found to be lower than other specimens. The stiffness of specimens having "boxed" configuration was found to be higher.

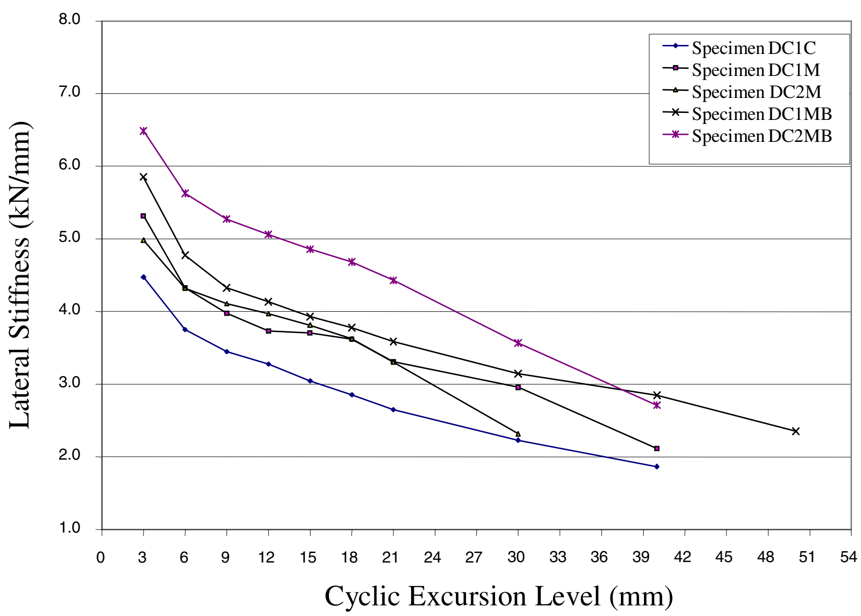


Figure 9: **Comparison of Lateral Stiffness of Specimens**

The stiffness of specimens having reduced batten spacing in plastic hinge region lies between the specimens with "boxing" configuration and specimen designed as per current code provisions. The additional batten plate in the plastic hinge region increases the stiffness of battened column. The additional batten plate of same configuration in the mid way of end panel of code designed battened column increased the initial stiffness by about 20% where as “boxing” configuration using a very wide plate in the end panel of specimen improved the stiffness by about 50%. The lateral stiffness of all test specimens was found to be reduced as the cyclic excursion level increases. The final stiffness of specimens just before failure is found to be about 40% of their corresponding initial stiffness. During elastic behavior, the degradation of lateral stiffness is rather steep and the rate of degradation of stiffness in inelastic range was small.

Moment-Curvature Response

The curvature at the section close to the fixed end is calculated from the strain measured at top and bottom fiber of webs of test specimens. The theoretical moment-curvature response of double-channel section is plotted in the Figure 10 and the moment-curvature response of test specimens are compared therein. The specimen designed as per code provisions showed that the specimen could able to reach percent of plastic moment and failed at a very low curvature. Specimens having reduced batten spacing in plastic hinge region showed the higher curvature before failure but it failed to reach its full plastic moment carrying capacity. In contrast, the specimens with “boxing” configuration of battens in the end panel were able to reach its full plastic moment capacity with sufficient curvature before failure. In summary, the reduced batten spacing in the panel of large bending moment improved the inelastic behaviour of the member.

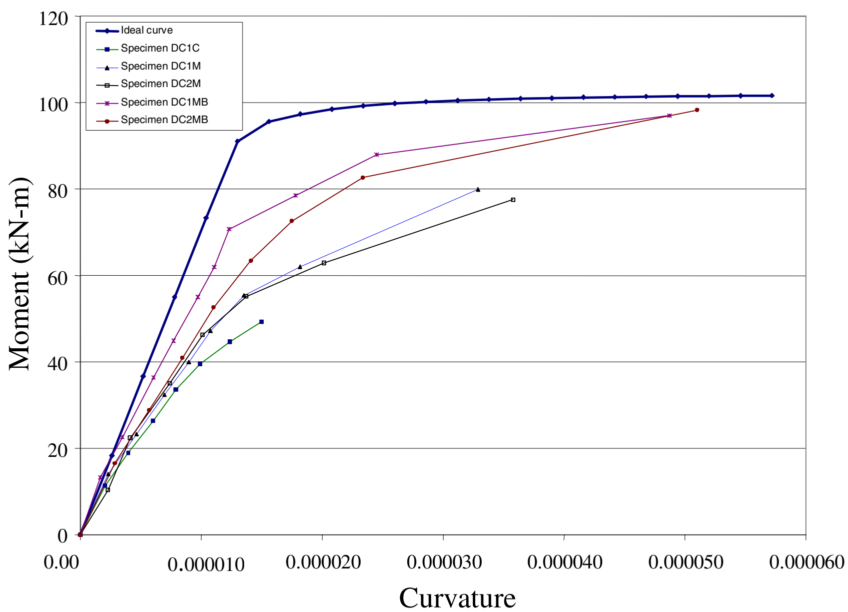


Figure 10: **Moment-Curvature Response of all Specimens**

Energy Dissipation Capacity

Figure 11 shows the cumulative energy dissipated by the test specimens at different cyclic excursion level. The energy dissipated by the test specimens at different excursion level was normalized to the energy dissipated at maximum peak displacement level (40 mm) and lateral load corresponding to full plastic moment carrying capacity of the section (100kN), considering elasto-plastic behaviour. The energy dissipated in each excursion level was calculated by average peak loads at three cycles to the corresponding lateral displacement.

The specimen DC1C showed the least energy dissipation in each cyclic excursion level and could reach about 65% of the ideal energy dissipation. The energy dissipated by the Specimen DC1M and DC2M was found to be higher than specimen DC1C and was about 80% of the ideal energy dissipation. Specimen having "boxing" configuration showed better energy dissipation capacity as compared to others. Hence, the energy dissipation capacity of battened column can be improved by reducing batten spacing in the panel of high moment.

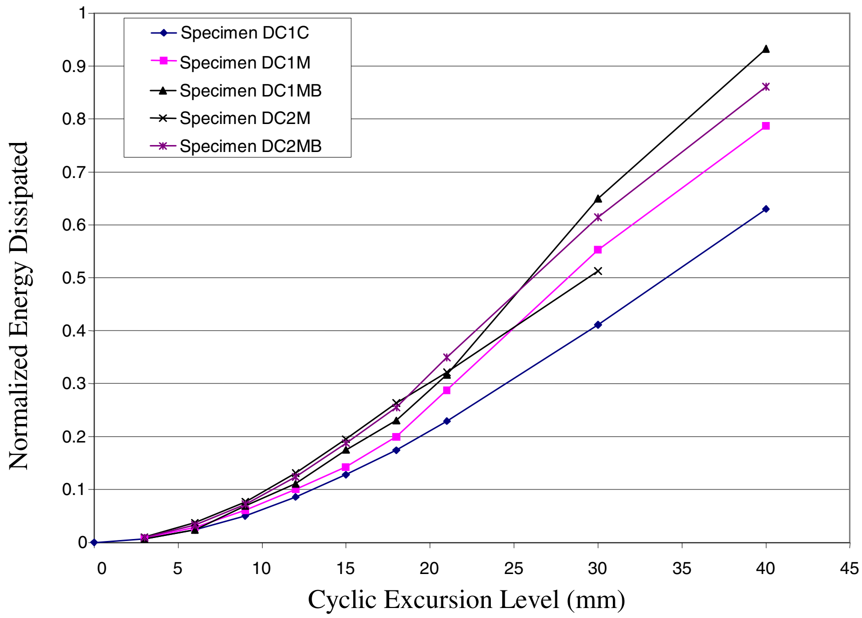


Figure 11: **Normalized Energy Dissipated at different excursion level of cyclic loading**

CONCLUSIONS

The battened double-channel columns designed as per current practice may behave satisfactorily in axial compressive loading. But during seismic overloads, the member may not be able to withstand the lateral load required to reach full plastic moment carrying capacity of section. The member may fail due to local as well as lateral instability in the panel nearer to fixed end prior to its full plastic moment capacity. Due to excessive compressive strain, the local instability of components in the form of web local buckling and flange local buckling may occur. It causes the closing of gap between components and the member may fail due to lateral buckling. Therefore, it is necessary that the design of battened member should be modified to behave satisfactorily during seismic overloads.

The battened member can carry more lateral load when the batten spacing is reduced to half of the conventional practice in the panel of high moment. The lateral stiffness and energy dissipated capacity of member can be improved. The member can undergo sufficient plastic rotation prior to collapse. The closing of gap between constituent components will not occur. However, the member may not able to withstand the lateral load which cause full plastic moment carrying capacity of the section and hence, the member should be strengthened further to carry more lateral load. The provision of half batten spacing in the plastic hinge region of battened double-channel beam-columns could perform better in terms of ductility demands, plastic rotation, and energy dissipation than the members having uniform spacing throughout. Hence, changing the batten configuration in the plastic hinge region, the ductile behaviour can be achieved to some extent.

The battened member having "boxed" region in the panel of high moment using a very wide plate may perform satisfactorily during seismic overloads. The lateral stiffness and energy dissipation capacity can be greatly improved. The member can undergo adequate plastic rotation prior to its failure. The member can be able to reach its full plastic moment carrying capacity without any kind of instability.

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