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# THE BEHAVIOUR OF BEAMS IN REINFORCED CONCRETE FRAMES UNDER THE COMBINED ACTION OF VERTICAL AND HORIZONTAL LOADINGS

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## SUMMARY

The object of this paper is to observe both analytically and experimentally the behavior of beams in reinforced concrete weak beam-strong column type of frames under the combined action of vertical and horizontal loadings, with the focus on the gradual increase of the vertical deflection along beam length due to the redistributions of internal forces under horizontal loading. It was found that it is necessary to limit the maximum value of interstory drift as least as possible by providing sufficient strength for buildings for the practical problems due to the considerable vertical deflection of the beams not to arise during and after earthquakes.

## INTRODUCTION

When a weak beam-strong column type of reinforced concrete frame is subjected to a series of reversed horizontal loading cycles along with a previously applied constant working vertical load on its beam, the two extreme ends of the beams gradually lose their rotational stiffness. The beams then gradually turn to behave like simply supported ones, by decreasing the fixed end moments and also by increasing the beam center moment. These phenomena result into the gradual increase of the vertical deflection along with the beam during the reversed horizontal loading. Now the practical problems that may arise due to this increase of vertical deflection along with the beam, are to have to use an uneven and deflected face of floors and roofs, causing ponding of water on roofs which may result in accelerated deterioration. And also for instance, the door and window panels may not be closed or opened properly during emergency etc(Ref.1). The possibility of these phenomena may be overcome by providing enough shear walls for the buildings to reduce the maximum interstory deflection angle during reversed horizontal loading. The aspect of this paper is to observe both analytically and experimentally the behavior of beams in reinforced concrete frames under the combined action of vertical and horizontal loadings (Ref.2).

Derivation of Analytical Model An analytical procedure is developed to suit the experimental study to be described in the following chapters, which deals with a series of statically one degree indeterminate, single-bay, single-story reinforced concrete frames, with two mechanical hinges at the bottoms of their both columns.

(1) The qualitative deflected shapes of the model specimens at the peak and at the end of the positive horizontal loading cycle are given in Fig.1(a) and Fig.1(b) respectively. The following equations can be reduced with the sign being taken clockwise.

$$\delta_{BL}=\mp\theta'\cdot\frac{L}{2} \qquad (1)$$

$$\delta_{BR}=(-\theta\pm\theta'-\theta'')\cdot\frac{L}{2} \qquad (2)$$

$$\delta_{CL}=(R-\theta)\cdot\frac{L}{4} \qquad (3)$$

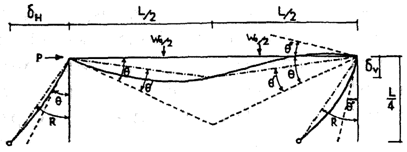
$$\delta_{CR}=(R-\theta'')\cdot\frac{L}{4} \qquad (4)$$

where, $\theta$ , $\theta'$ , $\theta''$ and R are the deflection angles as shown in the figures, and $\delta_{BL}$ , $\delta_{BR}$ , $\delta_{CL}$ , and $\delta_{CR}$ are the member deflections of the left half-length beam, left column and right column respectively. By using Eqs.(1)-(4) the interstory deflection angle R and the vertical deflection of the beam center become

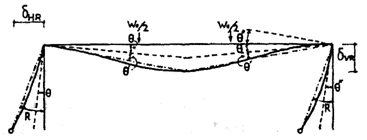
$$R=(-\delta_{BL}-\delta_{BR}+2\,\delta_{CL}+2\,\delta_{CR})\cdot\frac{1}{L} \qquad (5)$$

$$\delta_{v}=(\delta_{BL}-\delta_{BR}-2\,\delta_{CL}+2\,\delta_{CR})\cdot\frac{1}{2} \qquad (6)$$

(2) The frame members were divided transversely into the short elements of desired numbers to form a linear mesh of finite elements, which are connected to each other on their both ends, which was divided at an interval of 1 cm. Calculated M-$\phi$ curve, assumed hysteresis loop for section and yield hinge length are illustrated in Fig.2, Fig.3 and Table 1 respectively.



(a) At the Peak of Horizontal Loading



(b) At the End of Horizontal Loading

Fig.1 The Geometry of Deflected Shape ot the Specimens for Horizontal Loading

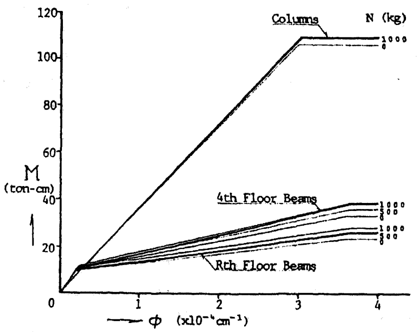


Fig.2 Calculated Moment-Curvature Relations

Table 1 The Comparison of Equivalent Yield Hinge Length Proposed by Different Authors(Ref.3)

| Proposer | Equivalent Yield Hinge Length, Lp | Calculated Lp (cm) for the Model Specimens |
|---|---|---|
| Baker | 2{0.8 $k_1 k_3$(z/d) c } | 21.0 |
| Mattock | 2(0.5 d+0.005 z) | 19.6 |
| Sawyer | 2(0.25 d+0.075 z) | 15.4 |
| Authors | dc/2+d (End)<br>2d (Center) | 18.2<br>25.6 |

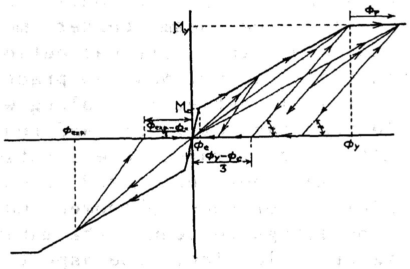


Fig.3 Degrading Stiffness Properties of Moment-Curvature Relations for Analytical Model

## EXPERIMENTAL STUDY

**Test Specimens** Two typical one-fifth scaled model specimens BS-41H and BL-61H were supposed to represent the Rth and 4th floor beams of the assumed prototype frames. Table 2 shows the variation of five specimens dealt with. To observe the effects of higher level of working vertical load, the specimen BS-61H was tested under an increased level of 45% of its ultimate vertical capacity without the experience of horizontal loading. The mechanical properties of materials used for the construction of the models are shown in Table 3.

Table 2 The Variation of Different Specimens

| Specimen | Longitudinal Reinforcement Ratio*(%) | | | Working Vertical Load | |
|---|---|---|---|---|---|
| | Baem | | Column | Wo | Wo/Wu |
| | End | Center | | (kg) | (kg) |
| BS-41H | 0.37 | 0.37 | 2.49 | 600 | 27 |
| BS-41V | | | | | |
| Bl-61H | 0.84 | 0.84 | | 1,070 | 33 |
| BS-61H | | | | 1,440 | 45 |
| BS-61V | | | | | |
| Stirrups & Hqops | pw=0.40%<br>3.2$\phi$ -50@ | | pw=0.42%<br>4.0$\phi$ -50@ | | |

* The same values for both tensile and compressive reinforcement

Table 3 Mechanical Properties of Materials

(a) Concrete

| Test Specimen | Comp. Strength | Young's Modulus |
|---|---|---|
| BS-41H | 0.28 | 230. |
| BS-41V | 0.35 | 220. |
| BL-61H | 0.28 | 220. |
| BS-61H | 0.28 | 230. |
| BS-61V | 0.28 | 240. |

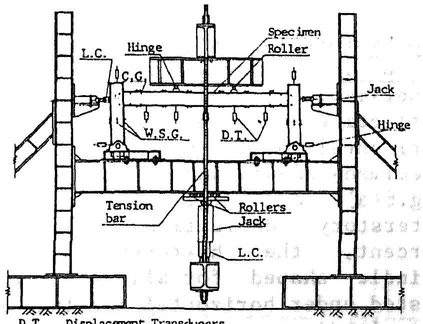
unit ; ton/cm²

(b) Reinforcement

| Bar | Yield Strength | Ultimate Strength | Young's Modulus |
|---|---|---|---|
| 3.2$\phi$ | 4.86 | 6.72 | 1900. |
| 4.0$\phi$ | 4.67 | 5.99 | 1900. |
| 6.0$\phi$ | 3.10 | 4.20 | 1900. |
| D10$\phi$ | 4.03 | 5.75 | 2100. |

unit ; ton/cm²

<ins>Loading and Measurement</ins> Three specimens with their numbers ending with the alphabets 'H'(eg.BS-41H) were tested under displacement controlled reversed horizontal load, during which there was a previous applied constant two points working vertical load (Wo) on the beam. At the end of the last cycles of horizontal loading, the vertical load on the beam was increased up to the failure of the beam in terms of three gradually increasing repeated vertical loading cycles in the case of 'BS' series. The other two specimens with the alphabet 'V' in their numbers were tested only under three gradually increasing repeated two points vertical loading cycles. Fig.4 shows the setup for the test with the loading and the measuring apparatus.



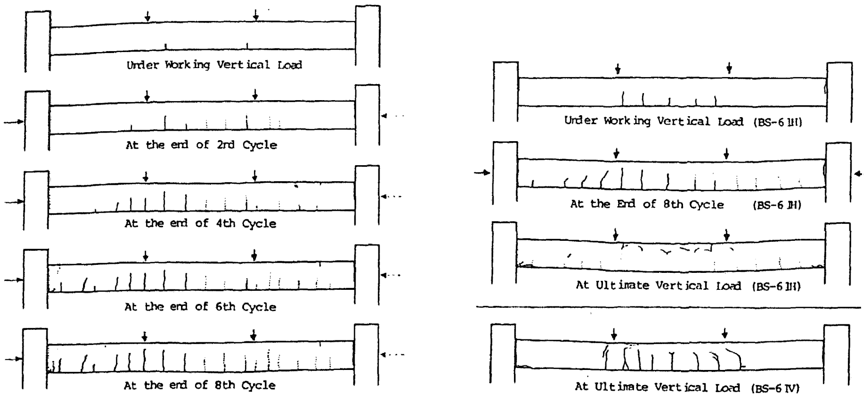
D.T. Displacement Transducers
L.C. Load Cells
W.S.G. Wire Strain Gages
C.G. Contact Gages

Fig.4 Set up for Loading and Measurements

## EXPERIMENTED AND CALCULATED RESULTS AND DISCUSSIONS

In this paper, focus is going to be placed on the 4th floor beam specimens, because the qualitative test results of the Rth floor beam specimens are more or less similar to their corresponding ones of 4th floor beam specimens.

<ins>The Crack Progress Observed on Beams during Horizontal Loading</ins> The crack patterns of BL-61H under working vertical load and at the end of the 2nd, 4th, 6th and 8th (last) cycles of horizontal loading are given in Fig.5(a). It was observed in the cases of all the specimens that the working vertical loading caused a few hair cracks on beams just under the two points of vertical load and or at the two extreme ends. With the application of reversed horizontal loading, the flexural cracks began to appear at the interval of 7-10 cm, starting from the bottom surface in the middle-third portion of the beam. As the interstory deflection angle was increased, these cracks began to extend deeper and wider inside the beam as new cracks appeared and spread on both sides along the length of the beam. On the other hand, on the top surface there appeared scarcely new cracks except those at and very near the two extreme ends of the beam. If the figures of cracks of both BL-61H and BS-61H at the end of the 8th cycle of horizontal loading in Fig.5(a) and Fig.5(b) are compared, it will be found that there are scarcely significant effects of the increased level of working vertical load on the crack patterns.

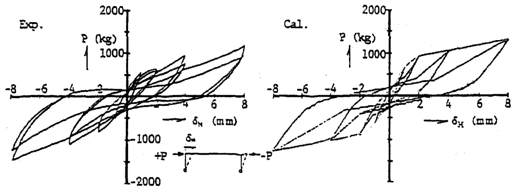


(a) BL-61H Under Various Loading Stages

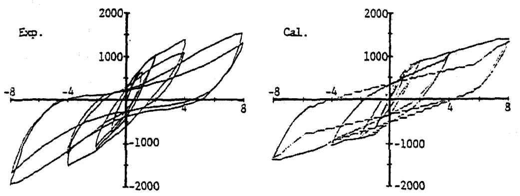
(b) BS-61H and BS-61V Under Various Loading Stages

Fig.5 Crack Patterns of Specimens under Various Loadings

**The Hysteresis Loops of Horizontal Load Versus Interstory Deflection Angle** The experimented and calculated load-deflection curves for reversed horizontal loading test of two different specimens BS-41H and BS-61H are given in Fig.6(a) and Fig.6(b). Up to the interstory deflection angle of 0.5 percent, the hysteresis loops were spindle shaped for all the specimens tested under horizontal loading. Then as the loading was increased beyond the deflection angle of 0.5 percent, the shape of the loops appeared to be of inverted 'S' type one. It can be seen from the comparison of these figures that the calculated curves resemble well enough the experimented ones. Thus the analytical method seems to be quite reliable for the prediction of the hysteresis loops under the combined loadings.



(a) BS-41H



(b) BS-61H

Fig.6 Experimented and Calculated Hysteresis Loops under Horizontal Loading

**The Increase of Vertical Deflection of Beam During Horizontal Loading** Fig.7 shows the vertical deflection progress at the center of the beam during reversed horizontal loading test (BS-61H). As it is seen in Fig.7, it was not possible to keep the working vertical load on the beam at its constant level during the horizontal loading tests. The vertical load, which was decreasing with the increase of the vertical deflection of the beams, was being readjusted at the end of every horizontal loading cycle. Fig.8(a) and Fig.8(b) shows the deflected shapes of the beam of BL-61H at the peak and at the end of reversed horizontal loading cycles respectively. As it is seen from these three figures, it was observed that vertical deflections along the length of the beams were increasing continuously during the reversed horizontal loading tests in the cases of all the three specimens. Moreover, it can be seen by the comparison between Fig.8(a) and

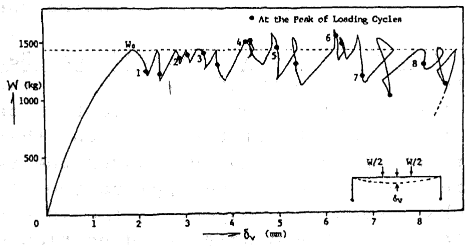
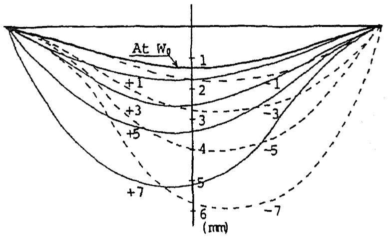
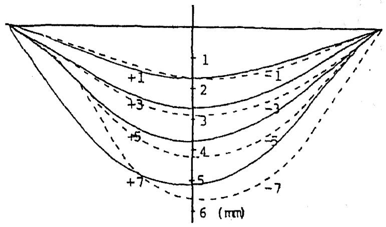


Fig.7 Progress of Vertical Deflection at Beam Center during Horizontal Loading

8(b) that the vertical deflections along the beams were not decreasing when the horizontal loading was withdrawn at the end of every positive and negative loading cycles. This increase of the vertical deflection of beams was more for the high level of applied working vertical load during the initial stages of horizontal loading. The experimented as well as the calculated values of the interstory deflection angle, R versus the beam half-length deformation angle, at the peak and at the end of every cycle of positive and negative horizontal loading of the three specimens are given in Fig.9. In this figure, the way of the progress of vertical deflection at beam centers during horizontal loading can be observed clearly. It is also seen that the calculated values obtained by the analytical method described above, lies between 80%-95% of the experimented values both at the peaks and at the ends of the horizontal loading cycles. Thus the method seems to be quite able to predict the progress of the vertical deflection at beam center under the combined loadings.



(a) At the Peak of Horizontal Loading Cycles



(b) At the End of Horizontal Loading Cycles

Fig.8 Deflected Shapes of Beams under Combined Loadings

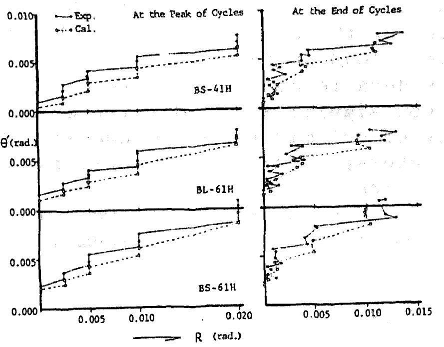


Fig.9 Experimented and Calculated Values of Interstory Deflection Angle Versus the Beam Half-Length Deformation Angle at the Peak and at the End of Horizontal Loading

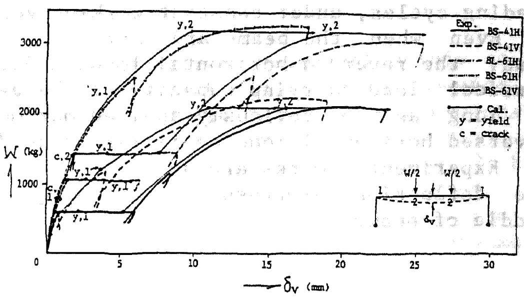


Fig.10 Load-Deflection Curves under Vertical Loading as well as the Progress of Vertical Deflection at Beam Center during Horizontal Loading

<u>The Vertical Load Carrying Capacity of Beams</u> Experimented and calculated load-deflection curves under vertical loading for all the specimens are given in Fig.10, in which the vertical load carrying capacity of the specimens with or without the experience of horizontal loading can be compared. The straight line portions of the curves extended horizontally are the effects of the increased vertical deflection during horizontal loading. The actual behavior

Table 4 Comparison between Experimented and Calculated Ultimate Vertical Loads

| | Ultimate Vertical Loads | | |
|---|---|---|---|
| Test Specimen | Exp. (kg) | Cal.* (kg) | Exp./Cal. (Ratio) |
| BS-41H | 2,090 | 2,030 | 1.03 |
| BS-41V | 2,190 | 2,030 | 1.08 |
| BS-61H | 2,970 | 3,120 | 0.95 |
| BS-61V | 3,200 | 3,120 | 1.03 |

* At collapse mechanism

of this portion for BS-61H was already given in Fig.7. It is seen that the reversed horizontal loadings have little effects on the ultimate vertical load carrying capacity of the beams in seismic-resistant ductile reinforced concrete frames. Table 4 and Table 5 show the calculated results.

Table 5 Calculated Values of Shear Capacity of Members and Boundary Sections(Ref.2)

| | Baem | Column | Boundary Section |
|---|---|---|---|
| Floor Frame | At Cracking<br>At Ultimate | At Cracking<br>At Ultimate | $\mu \cdot As \cdot \sigma y$ |
| Rth | 1,480<br>1,670 | 1,590<br>2,150 | 3,520 |
| 4th | 1,530<br>1,830 | 1,590<br>2,150 | 6,100 |

unit ; kg

## CONCLUSIONS

Based on the study reported herein, the following conclusions may be made.

1) The 1/5th scaled single-bay, five reinforced concrete frame specimens have been tested to study the behavior of the beams of frames under combined action of vertical and horizontal loadings. Two of the specimens were considered to represent the roof floor beam, while the rest three were to the 4th floor beam of a single-bay, six-story building, designed according to the RC Code of AIJ. With these specimens, the effects of the combined vertical and horizontal loads on the behavior of the frames have been observed. And also the effects of the increased level of the working vertical load during the combined loading have also been investigated.

2) It has been found from the experimental results that the reversed horizontal loading produces a considerable continuous progress of the vertical deflection along the length of beams, under working vertical load on the beam. It was also observed that the deflection become even greater at the ends of the horizontal loading cycles than those at the peaks of them.

3) The experimented results have been compared with those found from the calculations, using the analytical method. It has been found that this method is quite reliable for the prediction of the hysteresis loops and also the gradual increase of vertical deflection at the center of the beams during the horizontal loading cycles, under constant working vertical load on the beams.

4) Even when the beams are carrying a considerable amount of working vertical load, the reversed horizontal loading does not significantly affect the ultimate vertical load carrying capacity of the beams of seismic resistant ductile frames as long as the previously applied maximum interstory deflection angle caused by reversed horizontal loading is less than 2.0 percent.

5) Experimental works are now being done to develop an alternative way to control the deflection progress by increasing the amount of bottom reinforcement in the middle of beams.

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