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Frame-Bracing Interaction in Multi-Storey Buildings

Interaction de charpente et ancrages dans des bâtiments à plusieurs étages

Zusammenwirken von Rahmen und Verbänden in mehrgeschossigen Bauten

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1. Introduction

The bracing system in a multi-story building frame is designed to serve three specific fractions: 1) to prevent overall frame buckling under gravity load, 2) to resist story shear when the frame is subjected to combined gravity and lateral loads, and 3) to control lateral deflection (or drift) of the frame (1). Approximate methods for selecting bracing sizes are available in the literature (1,2,3) and are used in design practice. In these methods, it is generally assumed that the frame itself resist only the gravity load and that the bracing system is required to carry all the shear existing in a given story. No interaction between the frame and the bracing system is considered.

At low levels of applied loads, the frame would usually remain elastic and the interaction problem can be examined by using any conventional method of structural analysis. In a tall building frame, however, the presence of the secondary moment (or P-Δ moment) may cause the structure to respond non-linearly and a second-order analysis is required in order to determine the exact manner of interaction. The complexity of the interaction problem increases at high load levels when the frame becomes partially yielded. Any yielding in the frame tends to reduce its overall stiffness. A change in the distribution of the story shear between the frame and the bracing system will take place.

An analytical and experimental study has been carried out to investigate the interaction problem in low multi-story steel buildings. The study considers the behavior of diagonally braced frames in the elastic and elastic-plastic range and up to the maximum load. This discussion is a brief summary of the experimental program and the results obtained from two frame tests. Some analytical results related to the test frames are also included.

2. Test Frames and Loading Program

The frames tested in the experimental study are full size three-story, two-bay welded frames fabricated from rolled wide-flange shapes. A total of four frames were tested, two of which were loaded by gravity loads only (Frame 1 and 2). The remaining two (Frames 3 and 4) were subjected to combined gravity and lateral loads. The description presented herein pertains only to the frames. The frames were designed by the plastic method (1), with the girders proportioned for 1.7 times the working dead and live loads. Figure 1 shows the member sizes, exterior and interior connections, and the fixed base details of the test frames. Theoretically speaking, all structural components (girders and columns) in the frames designed by this method would reach their maximum capacity at the same load. However, because of variation of cross sectional and material properties, it was not possible to exactly achieve this condition in all the tests. Nevertheless, based on handbook section properties and a uniform yield stress of 36 ksi (minimum specified yield stress of A36 steel) for all members, the design shown in Fig. 1 was closely balanced.

The diagonal bracing was designed as a tension system and the cross sectional area was determined to meet certain drift limitation. Because of clearances the bracing could not be placed in the plane of the frame. The total

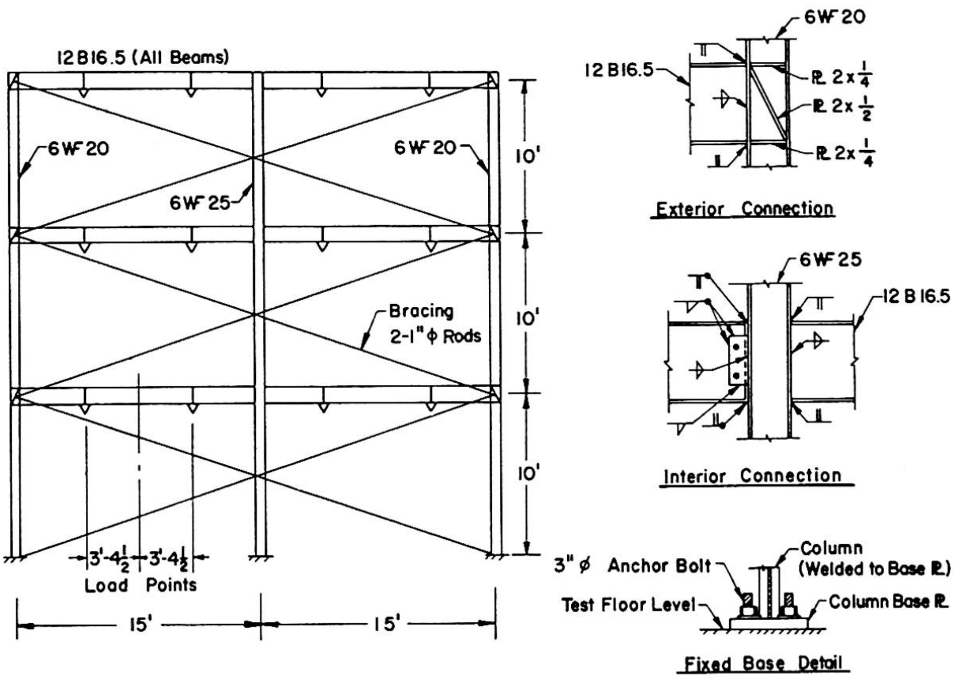

FIG. 1 TEST SPECIMENS

bracing area (1.57 sq. in.) was supplied by two, 1-in. diameter rods (slenderness ratio of 1520). One rod was placed on each side of the frame so that the resultant force would act in the plane of the frame. The bracing was prestressed before the testing operation to remove the sag and to offset slackening due to column shortening during testing. A detailed description of the fixtures used to attach the bracing to the frame and of the general test setup can be found elsewhere (4,5).

Although a pair of diagonal braces was provided in each story, only one was effective in resisting the story shear. This is because the slender braces used could sustain only a small compressive force. However, the "compression" brace in the test frame was made partially effective by the prestressing operation. A residual tensile force was present in all the braces after prestressing. When lateral loads were applied to the frame, both the tension brace and the compression brace would resist the loads provided that the net force in the compression brace was tensile. The compression brace eventually became ineffective when the net force changed to compression.

A checkerboard pattern of live loads was used in testing Frame 3. The loading pattern tends to produce a more critical bending moment condition (single curvature) in the interior columns. Frame 4 was tested with full gravity loads on all the girders. The loading conditions at the ultimate load of the two frames are shown in Fig. 2.

FIG. 2 LOADING CONDITION AT ULTIMATE LOAD

The loading program that was followed in testing Frame 3 consisted of four phases (Fig. 3):

Phase I Dead load on all the girders. The applied loads on the first and second floor girders increased from zero to 13.6 kips.

Phase II Checkerboard live load. The loads on the girders of alternate bays increased from 13.6 kips to 27.8 kips.

Phase III Wind load up to 4.5 kips applied at each floor level. All gravity loads were maintained at 13.6 kips or 27.8 kips.

Phase IV Proportional increase of gravity and wind loads. At the end of Phase III, the loads had the approximate proportions shown in Fig. 2. These proportions were maintained until a maximum of gravity load of 35.4 kips was reached in the heavily loaded girders. At this load, the girders failed due to the formation of plastic mechanism.

The loads of 13.6 kips, 27.8 kips and 4.5 kips represent, respectively, the factored (load factor = 1.30) dead load, dead plus live load, and wind load.

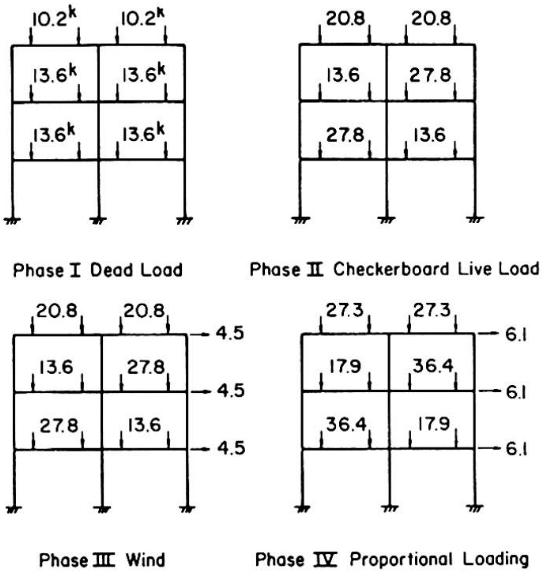

FIG. 3 LOADING PROGRAM FOR FRAME 3

For Frame 4, the load proportions shown in Fig. 2 were maintained throughout the test. The maximum girder load attained was 36.2 kips.

3. Theoretical Interaction in the Elastic Range

As elastic analysis of the test frames was performed to determine the theoretical interaction between the frame and the bracing system at low levels of the applied load. In general the amount of lateral load the frame resists depends on its stiffness relative to the bracing stiffness. The interaction of the test frame and various bracing sizes is illustrated in Fig. 4. The solid line on the right side shows the manner in which the total story shear is distributed between the frame and the bracing. For the bottom story, the sum of the frame shear and bracing shear must always equal 3.0 kips (neglecting any shear existing in the story induced by the secondary moment). Since the frame stiffness is assumed to remain constant, the theoretical interaction for various bracing areas will be a straight line. If the bracing is infinitely stiff, it will resist all the shear and the drift index Δ/h will be zero (point a). On the other hand, if the stiffness of the bracing is zero, then the frame will carry all the shear. In this case the frame is completely unbraced, and its Δ/h is equal to 0.0012 (point b). A straight line connecting these two points defines the frame bracing interaction. The solid curve in the left portion of Fig. 4 shows the relationship between the bracing area furnished and the resulting deflection of the frame. This curve is constructed by using the information (bracing shear and story deflection) given in the right portion of the figure. The dashed curve is based on the assumption that only the bracing resists the story shear.

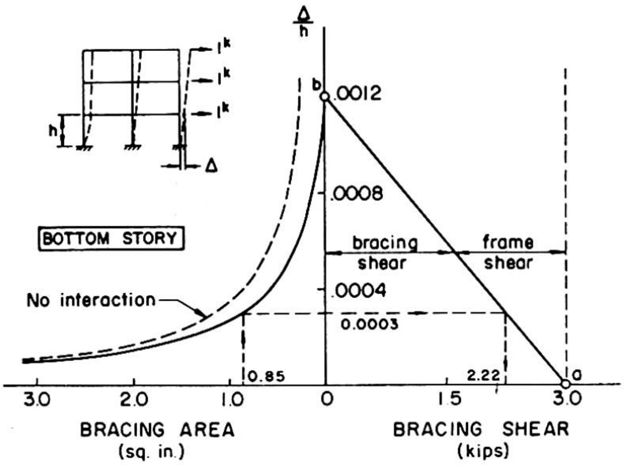

FIG. 4 THEORETICAL ELASTIC INTERACTION

The interaction between the frame and the bracing will change as soon as yielding takes place in the frame. The analysis presented above must be modified because of the reduction of frame stiffness caused by yielding. It is, therefore, necessary to know the locations of the plastic hinges before performing the analysis.

4. Experimental Results

Frame 3 - Lateral Loading Program (Phase III): As explained in Section 2, the lateral loads in Frame 3 were applied after a checkerboard pattern of factored gravity loads had been placed on the girders. The gravity load factor used was 1.30. Since the frame was designed for a load factor of 1.70, no plastic mechanism was expected to form in any of the girders at the beginning of the lateral loading program. There was, however, yielding in several parts of the heavily loaded girders near the interior columns. One plastic hinge formed in the first floor girder at a short distance away from the interior connection.

Figure 5 shows the shears developed in the columns and the bracing in the bottom story along with the total applied wind shear and the secondary shear caused by P-Δ moment. The bracing did not resist all the applied shear because

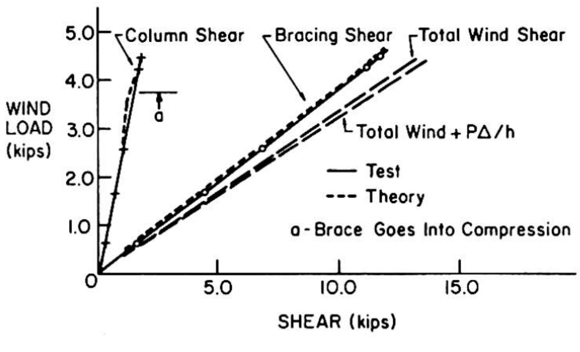

FIG. 5 RESULTS OF FRAME 3 TEST
(LATERAL LOADING)

of the frame resistance. The theoretical shears carried by the frame and the bracing are shown by the dotted curves, and the theory shows excellent with the test results. The theory considers the effect of yielded zones developed during the application of the gravity loads. The calculations show that the frame stiffness is reduced about 25% by yielding. This reduced the contribution of the frame in resisting story shear from 14% (elastic frame) to 12% when all braces are in tension. Point a in Fig.5 denotes the points at which the "compression" brace goes into compression, and the frame resistance increases to 22%.

Frame 3 - Proportional Loading Program (Phase IV): The final loading phase was the application of loads in the proportions shown in Fig. 2. The applied wind shear with the corresponding shears in the columns and the bracing for the bottom story are shown in Fig. 6. The P-Δ shear at maximum load amounts to about 9% of the total wind shear. The shear in the bracing is greater than the combined wind and P-Δ shears even though the frame should carry 22% of the total shear as observed previously. This is caused by the large shears produced by the gravity loads due to the formation of plastic hinges in the frame.

As plastic hinges form in an unsymmetrical manner, the frame becomes unsymmetrical and even symmetrical gravity loads will cause shear in each story. Figure 7 shows how the shear in the bottom story is increased as plastic hinges form due to the checkerboard gravity loads. The results are derived for a frame with an infinitely stiff brace (no sidesway). The test frame corresponds to case (c) at the start of the proportional loading. The theoretical shear produced is 6.96 times greater than the shear in the elastic frame. The shear due to the gravity loads corresponding to case (c) is shown in Fig. 6 added to the effects of wind and P-Δ. The gravity load shear amounts to 37% of the wind shear applied during the proportional loading phase.

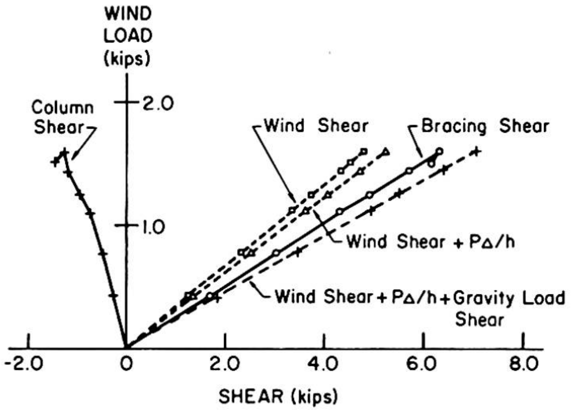

FIG. 6 RESULTS OF FRAME 3 TEST (PROPORTIONAL LOADING)

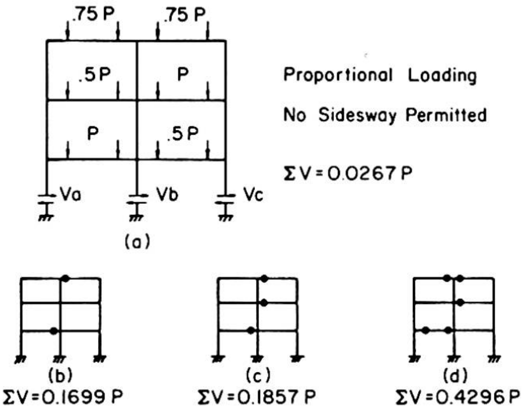

FIG. 7 GRAVITY LOAD SHEARS

Frame 4 - Proportional Loading: The frame was tested under proportionally increasing gravity loads and wind shear (Fig. 2). Because gravity loads were

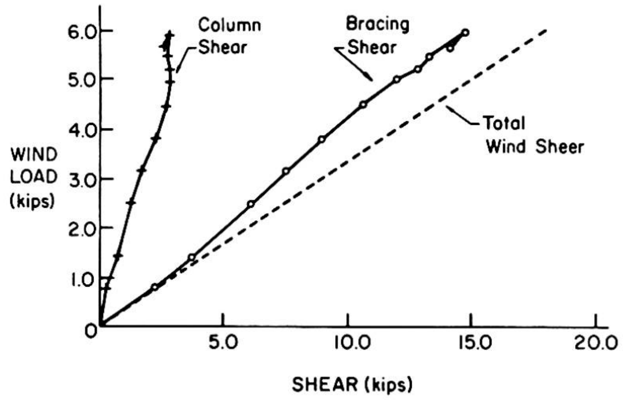

FIG. 8 RESULTS OF FRAME 4 TEST

applied symmetrically to all the girders the plastic hinge pattern developed in the frame was also symmetrical. The shear caused by the gravity loads was negligibly small. The results of this test, as shown in Fig. 8, are similar to those obtained from Phase III of the previous test.

5. Conclusions

Based on the results of this study, the following conclusions may be drawn with regard to frame-bracing interaction in low multi-story buildings:

1. The use of diagonal bracing is a very effective way to control drift and the reduce instability effect (P-Δ moment).

2. The amount of total story shear carried by the frame is significant (amounting to 20 to 30% of the total shear for the test frames).

3. In the elastic range, the distribution of story shear between the frame and the bracing system is nearly constant and can be predicted by conventional structural theory (instability effect need not be considered).

4. In the inelastic range, there is a tendency for the bracing shear to increase. This is due to the reduction of frame stiffness caused by yielding.

5. Under unsymmetrical gravity loads, the force to be resisted by the bracing system may exceed the applied story shear. Because of the gravity loads an additional shear of significant magnitude may develop in the columns after the frame is partially yielded in an unsymmetrical manner.

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Summary

The results of an analytical and experimental study on the interaction between a rigid frame and its internal bracing system are presented. The study pertains to low multi-story steel frames subjected to combined gravity load and wind. It is shown that the amount of story shear carried by the bracing depends on the relative stiffness of the bracing to that of the frame. The ratio between bracing shear and frame shear changes significantly when the frame is stressed into the inelastic range.