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Proposal for the investigation of instability of multi-story frames, 1962

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PROJECT 276

PROPOSAL FOR INVESTIGATION OF INSTABILITY OF MULTI-STORY FRAMES

by

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1. INTRODUCTION

In plastic design of multi-story frames, the members are proportioned by a criterion based on the load leading to the formation of a failure mechanism. However, it is possible that the frame may buckle at a load much smaller than the ultimate load corresponding to the failure mechanism. Therefore instability problems may govern the design of multi-story frames. According to the results of some single story rectangular frame tests, the load-carrying capacity of a frame is only 80 to 90% of the plastic load.(1) It is believed that the situation would become more serious when the number of stories is increased.

The problem of frame instability in tall building frames is becoming increasingly important because of recent developments in the fields of materials, architecture, and structures. Lighter building materials, modern curtain walls, the plastic method of design, and composite design of the floor systems, all contribute very much to the reduction of dead load on frames. On the other hand high-strength steels and improved methods of design as adopted in the new AISC Specification further contribute to the reduction of the member size. Consequently the slender column design gives rise to the more dangerous problem of frame instability.

From the point of view of structural design, the reduction in dead load, magnifies the importance of wind load which is considered as an important factor in the problem of frame instability. Therefore a simple frame subjected to working vertical load and varying horizontal load should be investigated as a preliminary study into the behavior of multi-story frames subjected to wind loads as well as vertical loads.

It is well known that bracing in building frames, and partition walls provide considerable sway resistance to the structures. Braced frames under vertical loads tend to buckle in a symmetrical configuration which corresponds to a higher buckling load then that of an anti-symmetrical configuration. Moreover, the bracing provides the most effective means for resisting horizontal load applied to frames. Therefore the investigation should include the solution of braced frames for determination of the minimum bracing requirement.

According to a literature survey,[2] there is no exact theory to analyze the instability problems of multi-story frames in the inelastic range. Furthermore, large scale instability tests are also needed. Therefore this proposal includes the development of theory, its experimental verification, and preparation of a recommendation for an approximate method of checking the stability of frames.

2. STATEMENT OF THE PROBLEM

There are many factors which affect the buckling load of a frame. It is essential to understand clearly each of these variables before the type of the frame instability problem can be classified. Once the individual type of problem is formulated, the suitable variables can be chosen for investigation according to practical necessity and their importance.

The factors affecting frame instability loads are the following:

(1) Slenderness ratio of columns $\frac{h}{r_c}$. This is the most important factor governing the buckling load of a frame.

(2) Stiffness of beams

The stiffness of beams is the second important factor. For example, frames with beam stiffness approaching zero can buckle regardless of the stiffness of the columns. This suggests that the stiffness of the floor slab be included for economical analysis, particularly in the case of composite design.

(3) Degree of restraint at supports.

Pined, partial-fixed or fix-ended conditions have substantial influence on the critical load of a frame.

(4) Types of steel.

Since the stress-strain curves and moment-curvature relations vary with different types of materials, the buckling loads of frames differ accordingly.

(5) Cross-sectional shapes

Only wide-flange shapes with typical residual stress patterns will be investigated.

Terrible format

(6) Loading conditions

Whether the loads are symmetrically applied or whether they produce primary bending moment in the frames are all important factors. Though the structure might be in the most critical state when possible dynamic loads are applied, the investigation of the effect of dynamic loads is not included in this proposal.

(7) Loading sequence

In the inelastic range, the behavior of a structure is non-conservative in its nature. Therefore the final status of the structure depends on the loading history. For proportiionally increasing vertical and horizontal loads on a frame, no strain reversal would occur in its members. However, a structure may undergo unloading in some part of the members, if the vertical loads are applied first and then the horizontal loads follow.

(8) Existence of shear wall or bracing.

In actual building frames, the walls or even partitions help resist sway considerably. The effect of bracing can enforce the frames to buckle in symmetrical modes which result in much higher critical loads than anti-symmetrical modes.

Types of frame instability are classified according to their loading conditions in Figure 1.

Type A is characterized by the bifurcation of equilibrium position at the critical vertical load. Since it is an initial motion problem, strain reversal will not be an important factor for evaluation of the buckling load. If the loads are not symmetrical, horizontal deflection develops immediately after the vertical loads are applied as shown in Type B. Type C is characterized by the application of proportional horizontal and vertical loads. This is a typical problem to be found in most of the literature. However, type D is a more practical situation. The frames under vertical loads are subjected to gradually increasing horizontal loads. The windward corners will undergo considerable strain reversal. To neglect this effect would result in a conservative analysis. However its quantitative picture is totally unknow. Therefore it is necessary to investigate this phenomenon.

When the frame is prevented from sidesway by bracing, the instability mode is always symmetrical (shown as type E). Methods for determining the ultimate strength corresponding to this type of failure are being developed in connection with the multi-story frame project. (273)

3. PROPOSED THEORETICAL STUDIES

The theoretical solution of frame instability problems becomes very complicated due to the high degree of indeterminacy, non-linearity of thrust-moment-curvature relationships, and the non-conservative nature of the structures in the inelastic range. However the problem can be solved by systematic investigation of the individual column and beam elements of which the frames are composed. Therefore column and beam deflection curves, and end-moment vs. end-rotation curves for various axial load and end-translations should be developed. In order to solve problem type D described in the previous section, the effect of unloading due to sway displacement should be included in analyzing the columns. For the sake of accuracy and efficiency, computer programming will be developed as much as practical. With these data available, it is possible to develop a method which is feasible for an accurate solution of frame stability problems.

However, it is necessary but not sufficient to develop an accurate theoretical method. A fairly simple approximate method should be recommended for practical design purposes. Unless the true behavior of frames is explored theoretically and confirmed by experiments, it is not adequate to estimate and recommend any approximate method of analysis. Moreover a purely experimental approach to investigate all variables would result in a tremendous number of tests. Therefore, it is essential to develop a general theory to analyze the structure under various loading conditions. The proposed theoretical studies can be summarized as follows:

(1) Completion of individual column and beam data curves.

Before the problem can be solved, more information about the individual columns and beams are necessary. Preparatory work includes the following items:

(a) Column deflection curves

(b) Column end-moment vs. end-rotation curves

(c) Beam deflection curves

(d) Beam end-moment vs. end-rotation curves

(e) Item (a) includes the sway effect

(f) Item (b) includes the sway effect

(2) Development of methods for analyzing partially yielded frames.

Elastic-plastic analysis of frames can be performed by using data (a) to (d) inclusive. Moment, rotation and deflection of members throughout the frames are to be determined by these data under any symmetrically applied vertical loads. Therefore the method can be used as the first step to the solution of problem type A. By repeating the process for different vertical load, problem type E could also be solved.

(3) Analysis of frames with bifurcation type instability.

A method will be developed to solve the buckling of frames under vertical loads. (shown as type A in Article 2). At first the frame is analyzed by the previously-mentioned method of elastic-plastic analysis under an assumed vertical load. Then the frame will be checked against sidesway buckling based on the data (e) and (f) listed in item (1). If the frame is found to be safe under the assumed load, a higher load is assumed and the process is repeated until a violation of the stability criterion occurs in any story of the frame.

(4) Analysis of frames with beam-column type sway instability.

The solution to problem types B and C will be treated using the data (e) and (f) listed in item (1). Literally the method is an elastic-plastic analysis of frames including the sidesway effect. Since there is no reversal of strain anywhere during the loading process, the solution is unique. The instability loads are characterized by the maximum points on the load-deflection curves. Actually the solution of problem (3) resembles that of the present problem. The difference between these two problems is that the sway deflection is real in one and ficticious in the other.

Before concluding the article, it should be pointed out that the proposed studies are oriented toward the following directions. First, for the sake of efficiency, accuracy and versatility, a digital computer will be used as much as practical. Second, the possibility of non-dimensionalizing the data will be investigated so that the results obtained from the 8WF31 section can be applied to any other WF sections. Third, the deformed shapes of frames, in particular, the position of the points of contraflexture in the columns, will be studied. Last, because of the possible advantage of extending the stability check to include the effect of dynamic load, an energy method will be attempted.

4. EXPERIMENTAL PROGRAM

Since there are so many factors affecting the frame instability load and some of their individual effects can not be investigated precisely by a purely theoretical method, experimental work is necessary. The theory can be applied for practical analysis only when it is verified by tests. However a purely experimental approach to investigate all variables would require a tremendous number of tests. It is believed that valuable information can be obtained by first conducting a series of carefully planned tests when enough progress has been made in the theoretical studies.

It is proposed that six model multi-story frames be tested. The proposed test program and its objectives are as follows:

(1) Unbraced frames under vertical loads

(Test frames U-1, U-2, U-3, and U-4) This series of tests, as shown in Table 1, is intended to check the validity of the theory of anti-symmetrical buckling of multi-story frames subjected to symmetrical vertical loads. The success of this series of test would also partly confirm the validity of the theory of symmetrical instability referred to as Type E in Article 2.

However, it has long been a question how much bracing is required in order to increase the vertical load up to the symmetrical instability load. Therefore the next series of tests recommended is:

(2) Braced frames under vertical loads

(Test frames B-1, and B-2) This series aims at the finding of the minimum requirements for bracing. At the same time it will check the validity of the theory of the symmetrical instability of multi-story frames. In other words, the test results will justify the method of elastic-plastic analysis proposed in the previous chapter. The series of tests is summarized in Table 2.

Depending on results of these tests and theory, the work will be extended to include the following investigations:

(3) Single frames under horizontal and vertical

loads

(4) Unbraced frames under horizontal and vertical loads

(5) Braced frames under horizontal and vertical loads

The loading system and test apparatus for the proposed tests are similar in principle to those reported in Ref. 1. The load will be applied on the frames by lever systems and dead weight. However some minor alternation and improvement are necessary. It is expected that difficulties will be encountered in alignment of the loading system for the tests of three-story frames. To remedy this, special devices will be attached to the lever system for adjustment of the load distribution on the frames.

Too vague to be useful

5. RECOMMENDATION OF A SIMPLIFIED METHOD OF ANALYSIS

Accurate analytical method and experimental verification are possible only for relatively simple frames. For highly indeterminate structures, such as tall building frames with a large number of bays, the precise analysis and test may not be feasible. Therefore a simplified method of analysis against frame instability is needed. The approximate method has to be based on some simplifying assumptions. The proposed studies should be able to evaluate approximately the error involved in each assumption, the approximate method can then be used to analyze more complicated frames with reasonable confidence. For example, the investigation of the effect of strain reversal, the measurement of angular change at each corner of the frames, measurement of deformed shape of frames, especially the position of inflection points, ---- all are oriented towards the justification of the assumpt-ions to be made in an approximate solution. Therefore the ultimate purpose of the proposed studies lies not so much in the theories and their verification but in the recommendation of a simplified method of analysis.

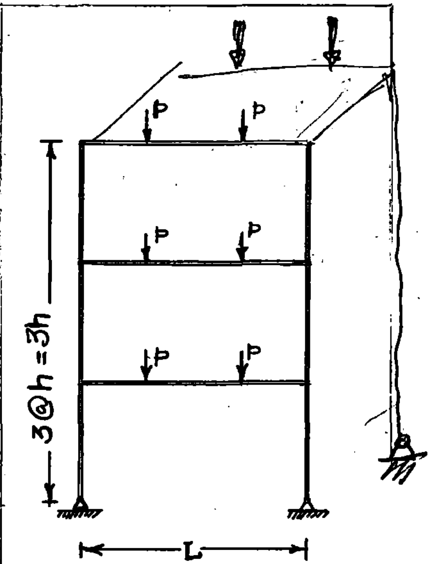
6. FINANCES

Enough funds have been included in the 1962-1963 proposal to cover planning and those tests that can be done in the current year. Costs of individual tests and total test program can not be certain until the test setup has been designed.

7. TABLES AND FIGURES

TABLE 1 PROPOSED TESTS OF UNBRACED FRAMES UNDER VERTICAL LOADS

Frame No.	Beam				Column			
	span L (in)	size	rx (in)	$\frac{L}{r_x}$	Height h (in)	size	r_x (in)	$\frac{h}{r_x}$
U-1	60	$2\frac{5}{8}$ I 3.7	1.095	54.8	33	$2\frac{5}{8}$ I 3.7	1.095	30
U-2	60	$2\frac{5}{8}$ I 3.7	1.095	54.8	44	$2\frac{5}{8}$ I 3.7	1.095	40
U-3	60	3 I 5.7	1.230	48.8	33	$2\frac{5}{8}$ I 3.7	1.095	30
U-4	60	3 I 5.7	1.230	48.8	44	$2\frac{5}{8}$ I 3.7	1.095	40



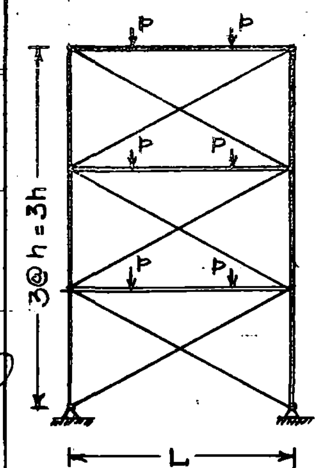
Note: Loads on beams will consist of either two or three concentrated loads.

⊗ All cols of same size?

TABLE 2 PROPOSED TESTS OF BRACED FRAMES UNDER VERTICAL LOADS

Frame No.	Beam				Column			
	span L(in)	size	r_x(in)	$\frac{L}{r_x}$	Height h (in)	size	r_x(in)	$\frac{h}{r_x}$
B-1	60	$2\frac{5}{8}$ I 3.7	1.095	54.8	33	$2\frac{5}{8}$ I 3.7	1.095	30
B-2	60	$2\frac{5}{8}$ I 3.7	1.095	54.8	44	$2\frac{5}{8}$ I 3.7	1.095	40

Note: The member size of bracing will be determined according to the instability load obtained from the previous unbraced frame test results.



(A) Symmetrical vertical loads

(B) Unsymmetrical vertical loads

(C) Proportional application of vertical and horizontal loads

(D) Constant vertical loads with varying horizontal loads

(E) Braced frame under vertical loads

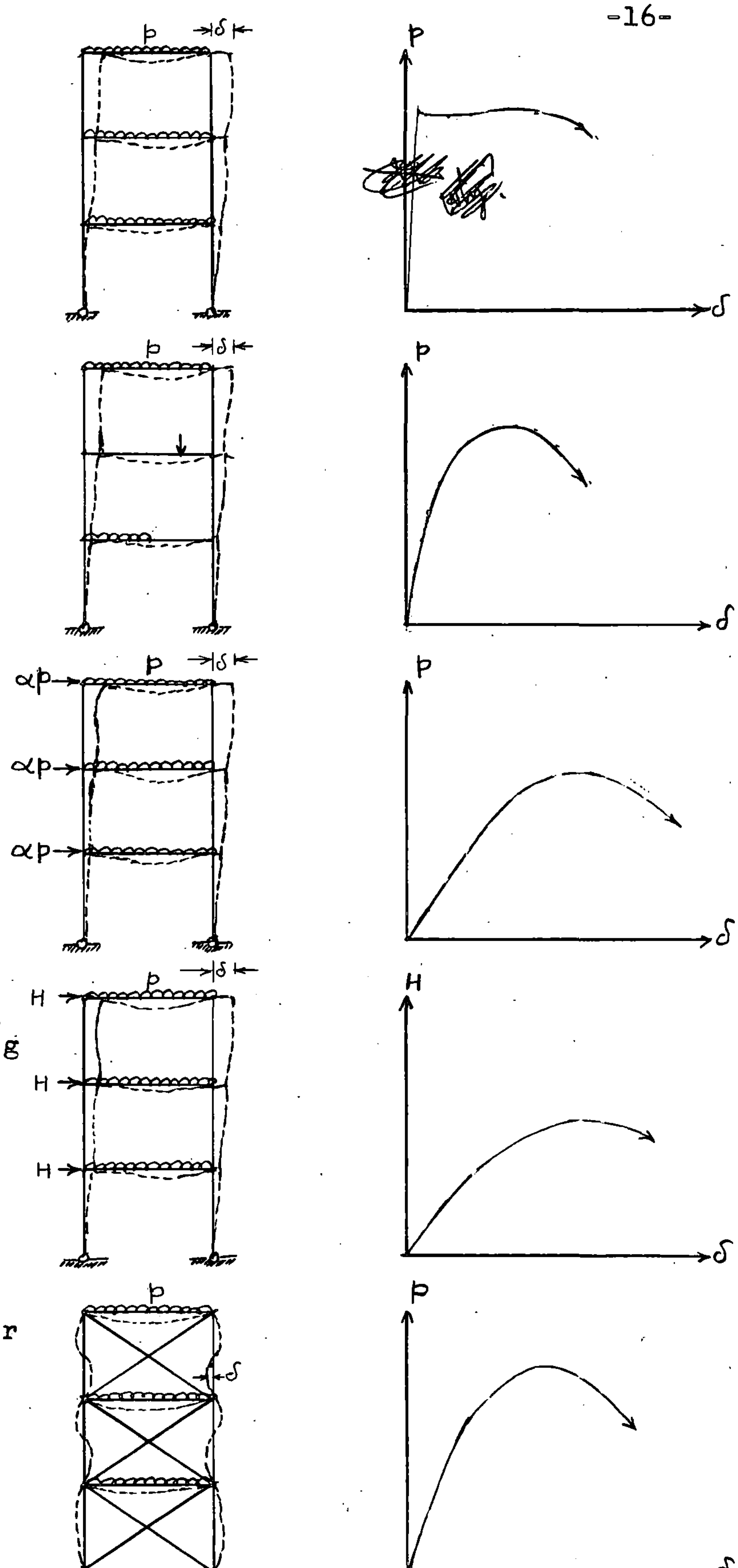


FIG. 1 TYPES OF FRAME INSTABILITY

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