Elastic-Plastic Analysis on the Behavior of Braced Frames under Repeated and Seismic Loading

by

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ABSTRACT

In this study, the braced frames is regarded as an assembly of elastic element, inelastic element and brace element. The elastic element has constant stiffness and the inelastic element is made of multi-spring, while the brace element is regarded as single-spring. The hysteresis rule for the inelastic element and brace element both are assumed. In view of these thinking, the elastic-plastic behavior of braced frames under repeated loading and seismic loading is studied. Two analytic examples for repeated loading and seismic loading are also given. The theoretical results for repeated loading agrees with the test results.

1. Introduction

Theoretical and experimental studies have been conducted to investigate the elastic-plastic behavior of braced steel frames in 1980s [(1)(2)(3)(6)], and some useful research results have been gotten. However in these theoretical studies so for, some shortages could be founded: (1) Using the precise FEM method, it is impossible for analyzing large scale frames, as the number of divided elements for analysis is too large[(6)]. (2) Separating braces and bare frames and setting up sharing ratio of horizontal forces between this two parts in advance, the real behavior of the braced frames cannot gotten[(3)]. (3) Ignoring the buckling effect in the hysteretic behavior of braces[(1)].

To overcome these problems, an analytical method is proposed in this paper. The steel beam-column is regarded as an assembly of elastic element, which the stiffness keep constant, and inelastic joint element, which is made of hysteretic multi-springs. While the brace is regarded as hysterestic single-spring (in the following it is called as brace element). Using these three kind of elements with two kind of assumed hysteresis models, the elastic-plastic behavior of braced frames under repeated and seismic loading is analyzed.

2. Analysis method

In this paper, the elastic element, the inelastic element and the brace element are

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combined for analysis. The inelastic element and the brace element are assumed having hysterestic behavior as followings:

(1) Hysteresis model for brace element

The brace is a truss element which is made up of single-spring and certain hysteretic behavior is assumed. Until now, many hysteresis models for brace have been proposed. In these models, the Wakabayashi Model is the one mostly agree to the test results. But in this model, the press force at the first stage of loading is greatly lower than that of test result. That is because the buckling effect has not been taken into account in this model. For this reason, the buckling effect is added in this hysteresis models for brace which is based on Wakabayashi Model.

The hysterestic curve for brace is divided into four parts (Stage A, B,C and D) shown in figure 1. Stage A is the stage that cross section of brace is yielding in tension. Stage B is the stage that brace is from bending to tension. Stage C is the stage that brace is bending suddenly. Stage D is the stage which the brace is in elastic loading or unloading. In this assumed hysterestic curve, the virgin elastic loading stage D0 is added at the Stage D. That is to say, Stage D0 is the elastic loading stage from loading start to brace virgin buckling, in which the initial stiffness keep constant. The virgin buckling strength is defined as the minimize volume of buckling strength about strong-axis and that about weak-axis.

(2) Elastic element

In elastic element, the effect of axial force to bending stiffness is considered. That is the geometrical nonlinearity ($p\delta$ effect) which is associated with with the sway deflection in element. The element stiffness matrix with 12 free-degree for geometric nonlinear analysis refers to reference [(5)].

(3)Hysteresis model for inelastic element

(a) The inelastic joint element consists of several axial springs and two elastic shear panel[(4)]. The skeleton curve of each axial spring in compression-side and tension-side are both made up of three lines as shown in Figure 2a. In the tension-side, the stages for elastic stiffness K_1, strain hardening stiffness K_2^T,and plastification are considered. In the compression-side the stages for elastic stiffness K_1, strain hardening stiffness K_2^C, and deteriorating stiffness K_3^C are arranged.

(b) In both the tension and the compression side, two imaginary points called by 'target point' are set up. Both target point is set at the elastic-limit point in the initial state. When a loading beyond the elastic-limit is made along one side of the skeleton with a certain amount of plastic deformation increment, the target point of the loading side moves together with the loading point. And at the same time, the other side of skeleton curve including the other target point shall be shifted to the loading direction as much as to the loading direction as ψ times the plastic deformation increment as shown in Figure 2b. The ψ volume for actual behavior of steel beam-column is from 0 to 1. In this study, ψ is used as 0.5.

(c) Unloading and reloading paths are modeled as portion of Ramberg-Osgood function shown in the Figure 2c.

(4) $p\Delta$ effect

The geometrical nonlinearity ($p\Delta$ effect), which is associated with with the nodal displacement, is considered. In the increment analysis, the Up-dated Lagrangian formulation is adopted to take into account the $p\Delta$ effect. The co-ordinate transformation matrix of member in the frame is deduced by the Euler rotation rule.

(5) Elimination of unbalanced forces

In the numerical analysis, the displacement control method for nonlinear is used. As the tangent stiffness before a increment step is approximately used as the one in the increment step, nodal unbalanced forces will exist at each load step. For elimination, the unbalanced forces at this load step are revised by adding the unbalanced forces to the force vectors in opposite direction in the next load step.

3. Example of analysis

(1) Elastic-plastic analysis under repeated horizontal loading

In 1975, an experiment study of braced frames under repeated horizontal loading is conduced at Wakabayashi Lab. of Kyoto University as shown in Figure 3a. The braced frames are made up of a rectangle bare frame and a brace, which is pin supported. In the top of right column, a repeated horizontal load is added. The programmed story drift angle versus the number of cycle of loading relation is shown in Figure 4. In this paper, by using these three kind of elements above the elastic-plastic analysis is made for this braced frames. The calculated results is shown from Figure 5a to Figure 7a. These calculated results show that it has fairly good agreement with the experimental results (Figure 5b,6b,7b) for the axial forces, the shear forces in columns and the loop shape of axial force in brace. Specially, the effect of the virgin buckling is reflected goodly from calculation. In this analysis, the total number of divided elements for using is only 13 as shown in Figure 3b, 4 for elastic element, 8 for inelastic elements and one for brace element. If general FEM method is used for analysis, 30 divided elements is necessary at lowest dividing for elastic-plastic analysis, in the case of each member is divided into six elements.

(2) Elastic-plastic analysis under seismic loading

Using the same braced frames above, the elastic-plastic analysis under seismic loading is also made. 20 ton joint mass is added at each top of the column. 10 sec record of EL-Centro seismic wave (1940) is used as input wave, which includes the major moving of the wave and the maximal acceleration is taken as 400gal. By 0.01 second time step, the time-historic analysis under seismic loading is carried out. The calculated results are shown from Figure 11 to 14. These calculated results show that the loop shape of axial force in brace and its virgin buckling strength are approximate to that under repeated horizontal loading.

4. Concluding remarks

(1) The elastic-plastic behavior of braced frames under repeated loading and seismic loading can be analyzed by using these three kind of elements (elastic element, inelastic element and brace element), in which few numbers of divided element are used.
(2) The assumed hysteretic characteristics for brace and inelastic portion of beam-column are suitable for the analysis of braced frames.
(3)The elastic-plastic analysis on braced frames under repeated loading by this method show that it has fairly goodly agreement with the experimental results for axial forces, shear forces in columns and loop shape of axial force in brace. Specially, the effect of the virgin buckling is reflected goodly from calculation.

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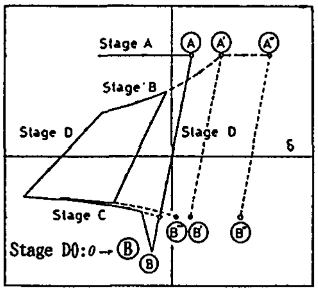

Fig. 1 Hysterestic rule for brace

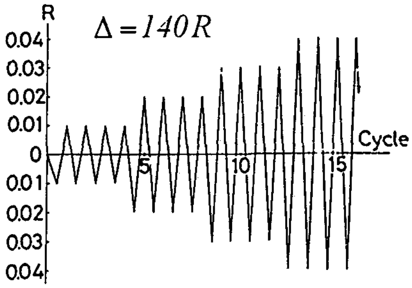

Fig. 4 Loading program

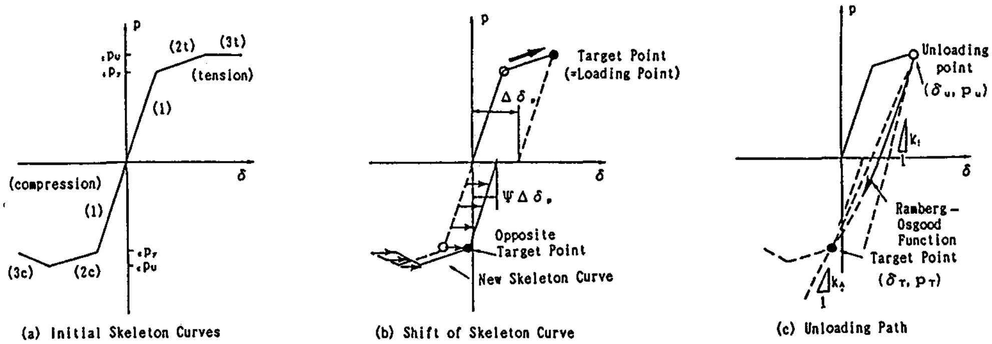

Fig. 2 Hysteresis rule for inelastic element (axial spring)

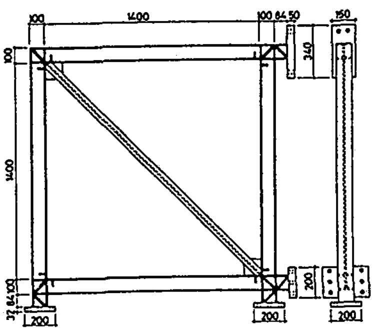

Fig. 3a Test setup (BFSI)

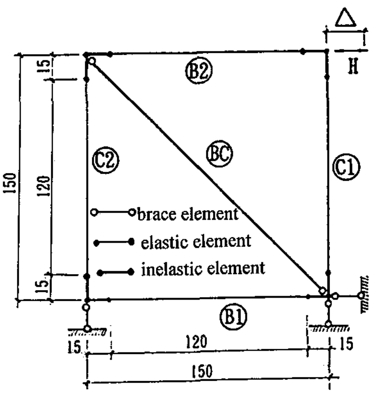

Fig. 3b Divided elements

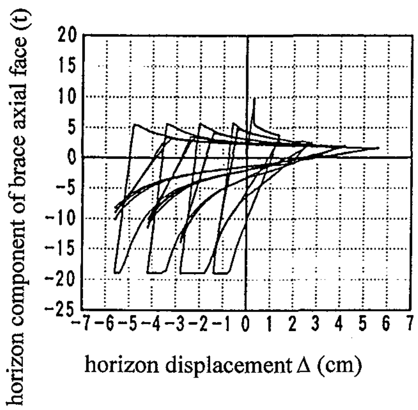

Fig. 5a Hysteretic behavior of brace (analysis)

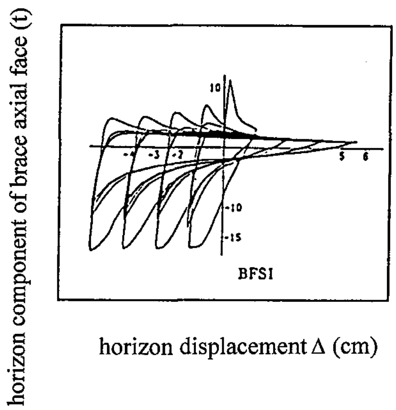

Fig. 5b Hysteretic behavior of brace (WB test)

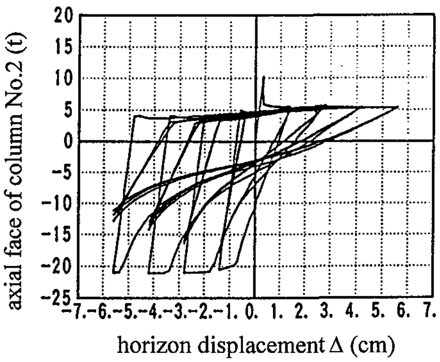

Fig. 6a Hysteretic behavior of column No.2 (analysis)

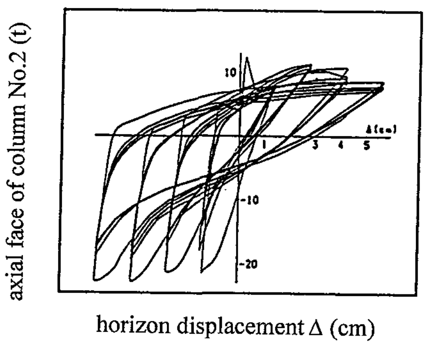

Fig. 6b Hysteretic behavior of column No.2 (WB test)

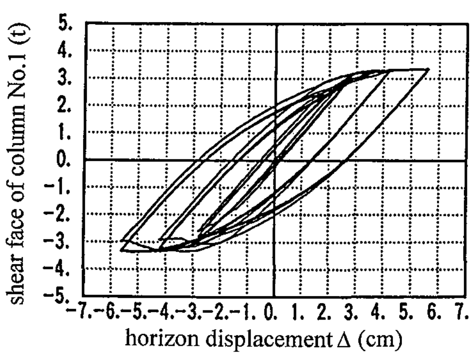

Fig. 7a Hysteretic behavior of column No.1 (analysis)

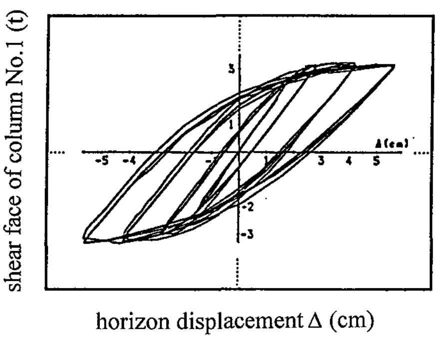

Fig. 7b Hysteretic behavior of column No.1 (WB test)

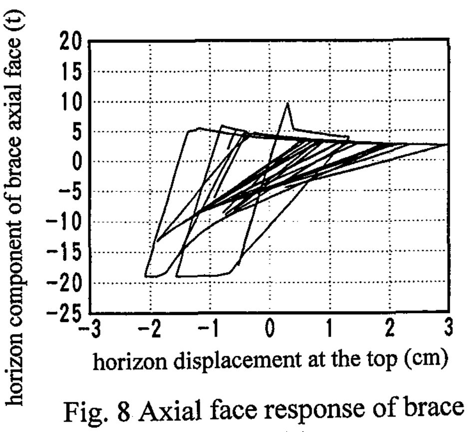

Fig. 8 Axial face response of brace (analysis)

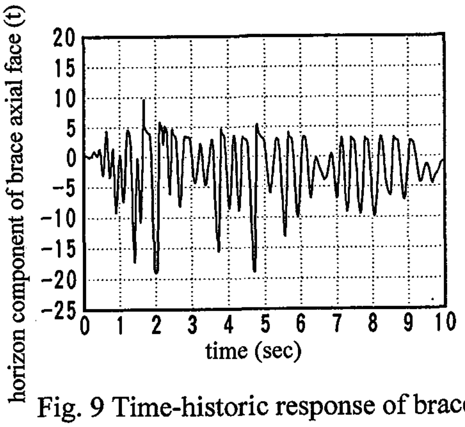

Fig. 9 Time-historic response of brace (analysis)

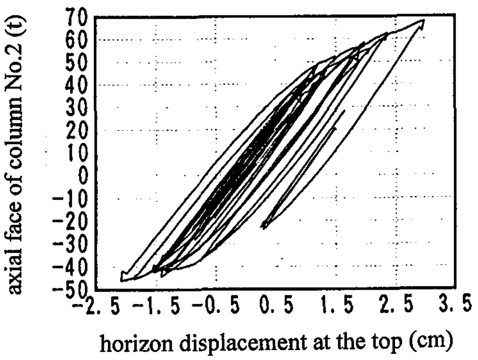

Fig. 10 Axial face Response of column No.2 (analysis)

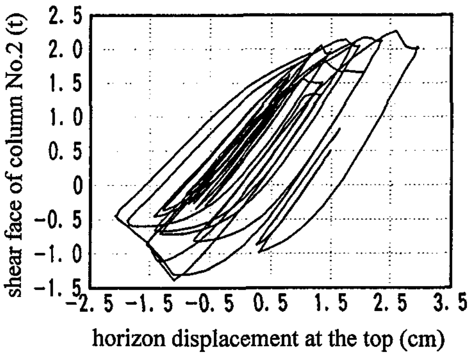

Fig. 11 Shear face response of column No.2 (analysis)