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PSEUDODYNAMIC TEST OF STEEL COLUMN WITH NONLINEAR CONNECTION USING SUBSTRUCTURING TECHNIQUE

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SUMMARY

Substructure-based pseudodynamic test technique is used for estimation of nonlinear earthquake responses of structural systems involving nonlinear substructures. Central differential method and constant acceleration method were employed as time integration procedure. As a practical application, we dealt with a steel member with a tension bolt connection.

INTRODUCTION

Pseudodynamic test is a direct test method for calculating nonlinear earthquake responses without large scale test. The experiment-analysis method is able to be used to determine loading conditions in various types of experiments automatically. Then, when we investigate cyclic behaviors of structures or structural members to earthquake excitation, loading conditions can be reasonably determined by the method and loading and measurement does not require any hand.

In 1969, Dr. Hakuno of Tokyo University proposed an idea of pseudodynamic test method. Review and future prospects on the method were discussed in some references [1-3]. In these references, it is stated that one of the systems actually realizing the idea of Dr. Hakuno is the substructure-based pseudodynamic test system, in which nonlinear restoring characteristics of substructures are measured.

Up to this time, a lot of pseudodynamic experimental systems were developed. However, almost of all were systems for complete structural systems. And in the extreme cases, a complete structure was modeled to a single-degree-of-freedom system and the same structure was actually loaded. Recently, substructure-based pseudodynamic test systems were reported by Katada[4], Iemura[5] and Dermitzaki[6]. Katada et. al. analyzed earthquake responses of multi-layered foundations including a liquefaction layer, of which restoring force characteristics were measured by dynamic tri-axial testing, by difference approximation of nonlinear equation of wave propagation. Iemura et. al. and Dermitzaki et. al. analyzed earthquake

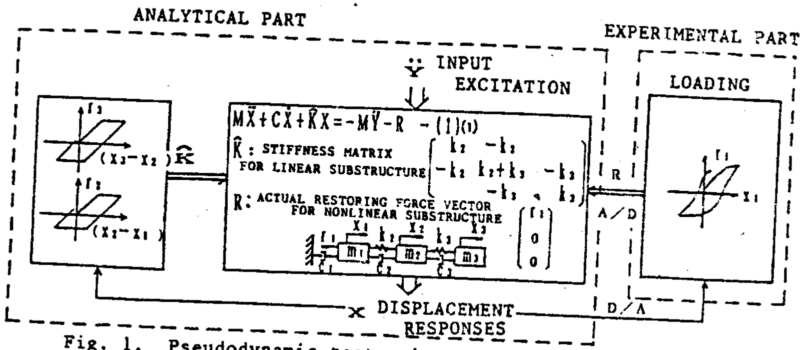


Fig. 1. Pseudodynamic test using substructuring technique

responses of multi story frames by means of the same kind of technique.

In this study, I developed a substructure-based pseudodynamic test system and analyzed earthquake responses of steel members with a tension bolt connection. Moreover I investigated the feasibility of numerical integration schemes which were able to be used for the system.

PSEUDODYNAMIC TEST USING SUBSTRUCTURING TECHNIQUE

Constitution

Figure 1 shows an outline of substructure-based pseudodynamic test system. The total system can be divided to an analytical part and an experimental part, and these two are connected by A/D and D/A converter. For instance, when we should calculate earthquake response of a three-story frame with a nonlinear story, whose restoring force characteristic can not be easily modeled mathematically, the governing equations of motion of the whole structure are initially solved numerically and the specimen, which is constructed in order to measure actual restoring force characteristics of the layer, is subjected to the displacement (x_1). Then the restoring force (r_1) corresponding to the displacement is directly measured from the test conducted in parallel to the numerical computation.

The actual restoring force vector (R) for the nonlinear layer is constituted with the restoring force value (r_1) directly measured, while stiffness matrix (K) of the other part of the structure can be made with linear stiffness coefficient (k_2) and (k_3). With the vector (R) and the matrix (K), we can calculate responses of the whole structure at the next step of time.

Time integration scheme

As the time integration scheme in order to analyze responses of the whole structure, I used the central differential method(CDM) as well as the Newmark-β method(β=1/4;constant acceleration method(CAM)). The CDM is one of standard integration methods for pseudodynamic experiments because of the explicitness, while the CAM is frequently employed in order to calculate dynamic responses because of the supreme accuracy as well as unconditional stability.

$$\left(\frac{1}{\beta(\Delta t)^2}M+\frac{1}{2\beta\cdot\Delta t}C+K\right)X_{i+1}=-M\ddot{Y}_{i+1}+Ma_i+Cb_i-R_{i+1}$$

$$a_i=\left(\frac{1}{2\beta}-1\right)\ddot{X}_i+\frac{1}{\beta\cdot\Delta t}\dot{X}_i+\frac{1}{\beta(\Delta t)^2}X_i$$

$$b_i=\Delta t\left(\frac{1}{4\beta}-1\right)\ddot{X}_i+\left(\frac{1}{2\beta}-1\right)\dot{X}_i+\frac{1}{2\beta\cdot\Delta t}X_i$$

$$\ddot{X}_{i+1}=\frac{1}{\beta(\Delta t)^2}(X_{i+1}-X_i)-\frac{1}{\beta\cdot\Delta t}\dot{X}_i-\left(\frac{1}{2\beta}-1\right)\ddot{X}_i$$

$$\dot{X}_{i+1}=\frac{1}{2\beta\cdot\Delta t}(X_{i+1}-X_i)+\left(1-\frac{1}{2\beta}\right)\dot{X}_i+\Delta t\left(1-\frac{1}{4\beta}\right)\ddot{X}_i$$

(a) NEWMARK-B METHOD ...(2)

$$\left(\frac{1}{(\Delta t)^2}M+\frac{1}{2\cdot\Delta t}C\right)X_{i+1}=-M\ddot{Y}_i-\left(K-\frac{2}{(\Delta t)^2}M\right)X_i-\left(\frac{1}{(\Delta t)^2}M-\frac{1}{2\cdot\Delta t}C\right)X_{i-1}-R_i$$

$$\Delta t\leqq 2/\omega_{max}$$

$$\ddot{X}_i=\frac{X_{i+1}-2X_i+X_{i-1}}{(\Delta t)^2}$$

$$\dot{X}_i=\frac{X_{i+1}-X_{i-1}}{2\cdot\Delta t}\qquad\ldots(3)$$

(b) CENTRAL DIFFERENTIAL METHOD

Fig. 2. Fundamental equations for a couple of time integration schemes

Figure 2 shows fundamental equations for calculating earthquake responses of the whole structures including nonlinear substructures by these integration procedures. Generally speaking, as an integration method for substructure-based pseudodynamic tests, unconditionally stable integration schemes such as the CAM is suitable, because multi degree of freedom systems are to be numerically analyzed. On the other hand, if we will employ the CAM as the integration scheme, we should predict actual restoring force vector (R_{i+1}) at the time (t_{i+1}), which has not measured yet at that time. In this study, I used following two vectors instead of (R_{i+1}); (1)restoring force vector (R_i) at the time (t_i), and (2)restoring force vector ($R^{(P)}{}_{i+1}$) predicted by using Lagrange's extrapolation for restoring forces measured at preceding three steps of time.

TESTING APPARATUS AND OBJECTS

Test specimen used is a steel H-beam with a tension bolt connection at the center of span length. Figure 3 shows configurations and dimensions of the test specimen. High tension bolts of F10T.M20 were used and tension force (18.2tonf) standardized on the specification was introduced to all of the bolts. I measured displacements at the center of span length, axial forces of

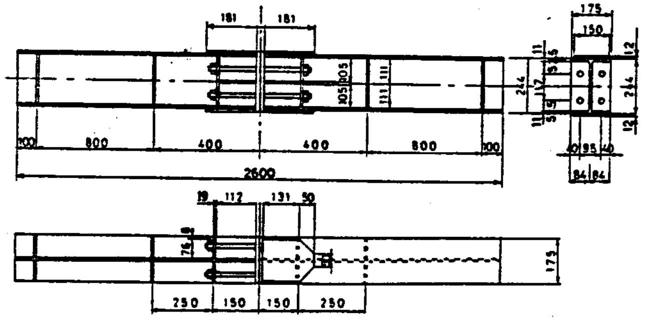


Fig. 3. Configuration and dimensions of steel beam specimen

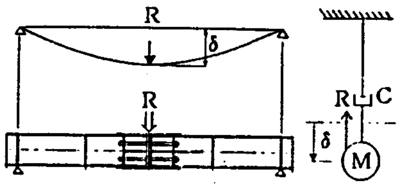


Fig. 4. Analysis object No.1

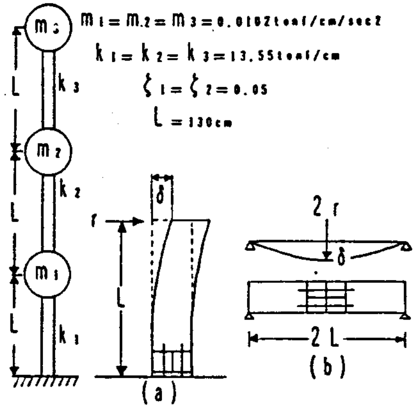


Fig. 5. Analysis object No.2

tension bolts and amount of separation at upper and lower flanges.

Firstly, as shown in Figure 4, to investigate basic features of the connection which I used, the simple steel beam with lumped mass at the center of span was modeled as a single-degree-of-freedom system and analyzed. The displacement at the center of span length was controlled for loading and corresponding reaction was measured as restoring force. In this case, the object which should be analyzed coincides with the specimen loaded.

Secondly, I analyzed a steel column with tension bolt connection at the base, as shown in Figure 5. In order to measure actual restoring force characteristic of the lowest story, reaction corresponding to center displacements of the specimen shown in Figure 3 were measured. Using the reaction (P), the restoring force can be calculated by the equation $r_1 = P/2$. Stiffness for the second and third story was initially measured and assumed to be constant. Then this example is an application of substructure-based pseudodynamic test system.

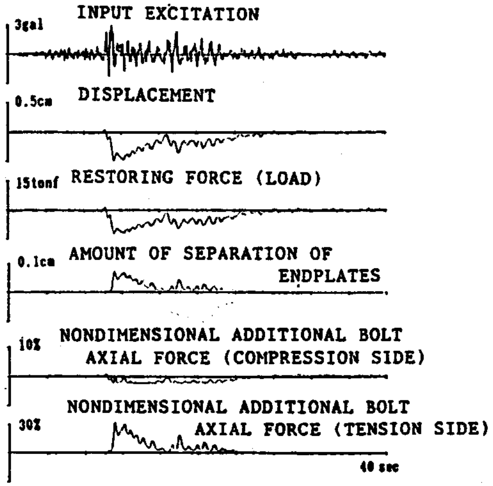
In this case, Rayleigh damping is assumed and the coefficients a0 and a1 were calculated from the following equations.

$$C = a_0 M + a_1 K \quad , \quad a_0 = \frac{2\omega_1\omega_2(\zeta_1\omega_2 - \zeta_2\omega_1)}{\omega_2 - \omega_1} \; , \; a_1 = \frac{2(\zeta_2\omega_2 - \zeta_1\omega_1)}{\omega_2 - \omega_1}$$

where ω_1 and ω_2 are natural circular frequencies for first and second vibration mode, and ζ_1 and ζ_2 are damping factors for these modes. Time step (dt) equals to 0.02sec which satisfies the condition of $dt \leqq 2/\omega_{max}$ (ω_{max} is maximum value of natural circular frequencies) to obtain a stable solution.

TEST RESULTS AND CONSIDERATIONS

Figure 6 shows time histories of the input excitation, displacement response, restoring force (reaction), amount of separation and additional bolt axial force divided by initial bolt axial force. Figure 7 shows relationships between restoring forces and displacement responses. When the input excitation reached to the peak value, end plates were separated and displacement increased remarkably. As a result, the additional bolt axial force of tension flange increased notably.



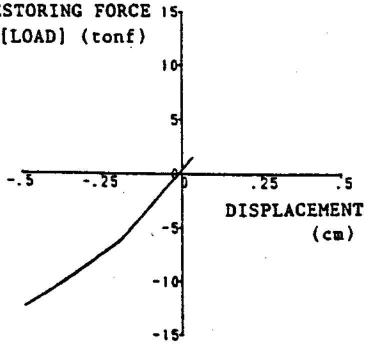


Fig. 7.
Actual restoring force-displacement relationship

Fig. 6.
Time histories of input excitation, displacements and measured values

The stiffness of the specimen decreased to 60 percent of the initial value. However, according to the decrease in the ground acceleration, the displacement was reduced gradually and at the end additional bolt axial force reduced to zero. It was concluded that the stiffness of the beam specimen which had been subjected to earthquake motion was nearly equal to the initial stiffness.

Figure 8 shows time histories of the ground acceleration and displacement responses in case that nonlinearity of the connection is neglected, while Figures 9 and 10 shows time histories of displacement responses estimated by substructure-based pseudodynamic experiments with the CDM and the CAM as time integration procedure, respectively. Figure 11 shows time histories calculated by the CAM where $(R^{(P)}{}_{i+1})$ obtained by the extrapolation technique is used as actual restoring force vector.

From these figures, I can say that
(1)maximum absolute value of displacement response at the nonlinear story which was obtained by the CDM was 20 percent greater than that value in case of the linear analysis,
(2)the value obtained by the CAM was 27 percent greater than that of the linear solution,
(3)extrapolation was effective for predicting actual restoring force, when we use the CAM as time integration procedure.

CONCLUDING REMARKS

In this study, I developed a substructuring pseudodynamic test system. As an application of the system, I analyzed a steel member with a tension bolt

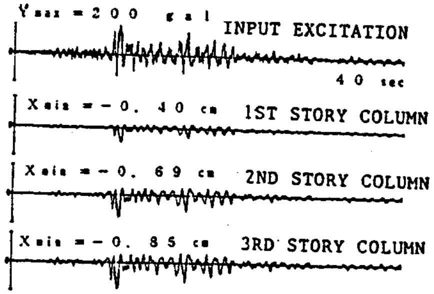


Fig. 8.
Time histories of input excitation and displacements in case of linear analysis

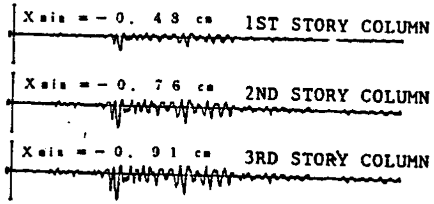


Fig. 9.
Time histories of displacements obtained by the CDM in case of nonlinear analysis

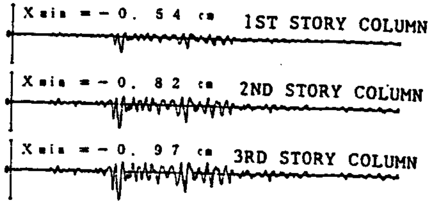


Fig. 10.
Time histories of displacements obtained by the CAM in case of nonlinear analysis

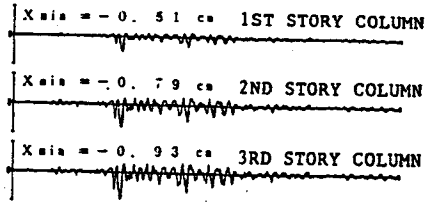


Fig. 11.
Time histories of displacements obtained by the CAM with the predicted ($R^{(P)}_{i+1}$) in case of nonlinear analysis

connection. The system developed here is applicable to various types of experimental investigations concerning cyclic behaviors of structural systems subjected to earthquake motions.

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