PSEUDO-DYNAMIC TESTS ON FRAMES INCLUDING HIGH STRENGTH BOLTED CONNECTIONS

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SUMMARY

Several examples of the earthquake response analysis done by the so-called "Computer-Actuator On-line System" have been reported. Here the on-line test results of the frames with bolted joints after slippage are reported, and a mathematical model for end moment-end rotation relationship in the beam with bolted connection is proposed. Then, the response behavior obtained using this model is compared with the on-line test results.

INTRODUCTION

High strength bolted friction type connections are frequently used in the beam to column connections of steel building structures, but the earthquake response behavior of the buildings after the bolt slip, which restoring force characteristics is extremely complicated, can hardly be predicted by an usual response analysis where a simple mathematical model is assumed. However, the pseudo-dynamic test can present the real response behavior. The principle and the procedure of the pseudo-dynamic test have already been reported (1). In this paper, a proposed mathematical model for the end moment-end rotation relationship in the beam with bolted connection and the computational method using this model are described.

MATHEMATICAL MODEL AND COMPUTATIONAL PROCEDURE

On the basis of the reversed and repeated tests of the beams with high strength bolted connection, a mathematical model (denoted by Bolt-slip model) is developed as shown in Fig.1. This model consists of a bi-linear type hysteresis loop, which describes the behavior before slippage, and a slip type hysteresis loop, which describes the behavior after slippage. At the earthquake response analysis of the frame using this model for the end moment M vs. the end rotation Θ relationship in the beam, the computational procedure when the slippage occurs is described as follows. For example, a frame as shown in Fig.2 is considered, and the mass of each story is concentrated at each floor level. When the slippage occurs at the connection in the beam of i-th story during the earthquake, the displacements at the floor levels $\mathbb{X}$ and the response velocities $\dot{\mathbb{X}}$ do not change, since the slippage occurs instantaneously, but the restoring forces $\mathbb{F}$ and the response accelerations $\ddot{\mathbb{X}}$ suddenly change. The joint rotations $\boldsymbol{\theta}$ are also changeable if the inertia of rotation is neglected. Here $\not{\mathbb{X}}$, $\dot{\not{\mathbb{X}}}$, $\ddot{\not{\mathbb{X}}}$, $\not{\mathbb{F}}$ are the values just before slippage, respectively. To content the conditions of equilibrium after slippage, the changes of the restoring forces, the moments, the displacements and the joint rotations by the slippage are related as follows;

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$$\begin{Bmatrix}\Delta \mathbb{F} \\ \Delta \mathbb{M}\end{Bmatrix} = [K] \cdot \begin{Bmatrix}\Delta \mathbb{X} \\ \Delta \theta\end{Bmatrix} \qquad \text{(Eq.1)}$$

where [K] is the stiffness matrix of frame excluding the stiffness of beam where the slippage occurs. Here the moment deterioration by the slippage $\Delta \mathbb{M}$ is given by bolt-slip model, and $\Delta \mathbb{X} = 0$. Then, $\Delta \mathbb{F}$ and $\Delta \theta$ can be calculated. Furthermore the restoring forces $\mathbb{F}' = \mathbb{F} + \Delta \mathbb{F}$ and the joint rotations $\theta' = \theta + \Delta \theta$ immediately after slippage will be calculated. After the slippage, the equations of motion must be holded;

$$\mathbb{m} \cdot \ddot{\mathbb{X}}' + \mathbb{C} \cdot \dot{\mathbb{X}} + \mathbb{F}' = - \mathbb{m} \cdot \ddot{\mathbb{y}}_0 \qquad \text{(Eq.2)}$$

where $\mathbb{m}$ and $\mathbb{C}$ are the mass matrix and the damping matrix. Here $\dot{\mathbb{X}}$, $\mathbb{F}'$ and the acceleration of the ground motion $\ddot{\mathbb{y}}_0$ are already known, then the response accelerations immediately after slippage $\ddot{\mathbb{X}}'$ can be calculated. Using these values $\mathbb{X}$, $\dot{\mathbb{X}}$, $\ddot{\mathbb{X}}'$ as initial values, an incremental calculation for integration of the equation is continued successively. For numerical integration of the equation of motion, the linear acceleration method has been utilized in this paper.

RESULTS OF ANALYSIS

The portal frames with a H-shaped steel beam and rigid columns with pinned feet as shown in Fig.3 are taken for analysis. The specific properties of the frames and the ground accelerations used in the analysis are summarized in Table.1. The results of the frames with bolted connections (denoted by FJ6) by the on-line analysis are compared with those of numerical analysis using the bolt-slip model, and the results of the frames without bolted connections (denoted by FJO) are compared with those by the bi-linear model. Here the parameters of bolt slip model are shown in Table.2, and the plastic stiffness of bilinear model is 20% of the elastic stiffness.

Some typical results are shown in Fig.4 to 6. The hysteresis loops of the end moment M vs. end rotation Θ relationship in the beams are shown in Fig.4, the time histories of response displacements in Fig.5, and Fourier spectra of response displacements in Fig.6. Each figure shows a set of the results in FJ6-II and in FJO-II. In Fig.5 and 6, the solid line shows the result by the on-line analysis and the dashed line shows that by the numerical analysis, respectively. The restoring force characreristics after slippage is very complicated, and the slippage of bolted connection causes the large response displacement and the vibration with the prolonged period. The response behaviors calculated using the bolt slip model show about the same change in the dynamic feature of frame after slippage as the on-line test results, and this model is recognized avaibable for rough estimation of such a response.

To see the influence of slippage, the maximum response displacement spectra and the absorbed plastic strain energy spectra calculated with the bolt-slip model are compared with those calculated with the bi-linear model. The analyzed frame is as shown in Fig.3. Some results are shown in Fig.7 & 8. The maximum response displacement spectra are shown in Fig.7, and the plastic strain energy spectra in Fig.8. These show that the difference between the maximum displacements calculated with the bolt-slip model and those with the bi-linear model is sensitive to the type of ground motion and the initial natural period of frame, but the difference in the absorbed plastic strain energy between two models is less sensitive.

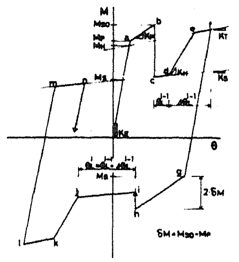
CONCLUDING REMARKS

(1) The slippage of bolted connection causes the sudden change in the dynamic features of frames. It causes the large response displacement and the vibration with the prolonged period.

(2) A proposed mathematical model is available for rough estimation of the responses of frames with slipped bolted connections.

REFERENCE

1. K.Takanashi et al., "Earthquake Response Analysis of Steel Frames by Computer-Actuator On-line System", Proc. of the 5th Japan Earthquake Engineering Symposium-1978.



Bi-linear ;Befor $|M|=|M_{S0}|$
b-c ;First slippage occurs at $M=M_{S0}$
c-d-e-f-g-h ;After First slippage
h-i ;Second slippage occurs at $|M|=|M_B|+2\cdot\delta M$
i-j-k-l-m-n ;After second slippage
Θ_L^i ;Slip length, $\Theta_L^i=\Theta_L^{i-1}+\Delta\Theta_L^{i-1}$

Fig.1 Model for end moment vs. end rotation (Bolt-slip model)

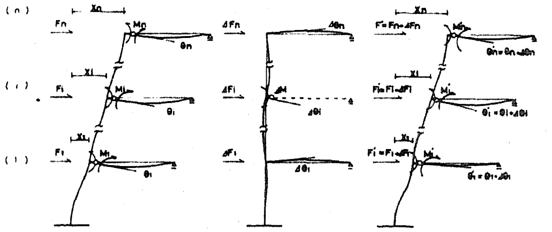

(a) (b) (c)

Fig.2 (a)Before slippage, (b)Changes of restoring forces & moment, (c)After slippage

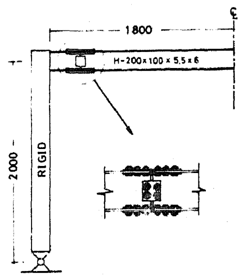


Fig.3 Analyzed frame

Table 1 Analyzed frames & ground motions

Frame	Beam	Structure					Ground Motion		
		X_p (cm)	M_p (t·cm)	K_E (t/cm)	m (t·sec²/cm)	To (sec)	α (gal)	α/α_p	TYPE
FJ6-I	BJG 63-9	1.56	607.2	3.903	0.0121	0.35	904.8	1.8	HACHINOHE NS
FJO-I	BJG 0-5	1.93	618.1	3.196	0.0099	0.35	918.45	1.48	
FJ6-II	BJG 63-12	1.87	662.7	3.536	0.0109	0.35	648.7	1.08	HACHINOHE EW
FJO-II	BJG 0-4	2.07	657.1	3.174	0.0098	0.35	643.2	0.96	
FJ6-III	BJG 63-13	1.92	661.1	3.450	0.0108	0.35	648.0	1.05	EL-CENTRO NS
FJO-III	BJG 0-3	1.98	653.8	3.297	0.0102	0.35	649.6	1.02	
FJ6-IV	BJG 63-16	1.99	650.4	3.276	0.0102	0.35	672.1	1.05	TAFT EW
FJO-IV	BJG 0-6	2.15	647.6	3.012	0.0093	0.35	671.6	0.97	

$X_p = 2\cdot F_p/K_E$, $F_p = M_p/H_c$, M_p ; Full plastic moment of beam, H_c ; Column length
$\alpha_p = X_p\cdot\omega_0^2$, $\omega_0 = 2\pi/T_0$, K_E ; Elastic stiffness of frame, T_0 ; Natural period
m ; Mass

Table 2 Parameters of bolt-slip model

M_{so}	M_H	M_s	K_p	K_s	K_H	K_T
$1.15 \cdot M_p$	M_p	$0.5 \cdot M_{so}$	$0.2 \cdot K_E$	$0.01 \cdot K_E$	$0.6 \cdot K_E$	$0.01 \cdot K_E$

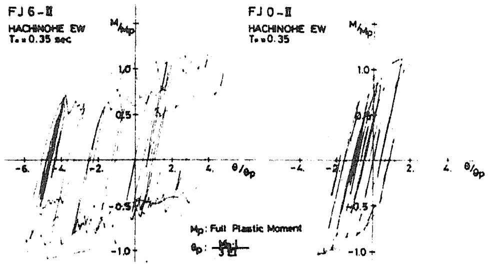


Fig.4 End moment-end rotation of beams

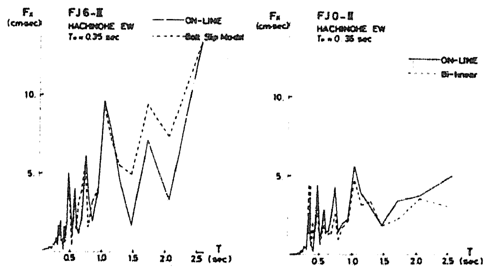


Fig.5 Fourier spectra of response displacements

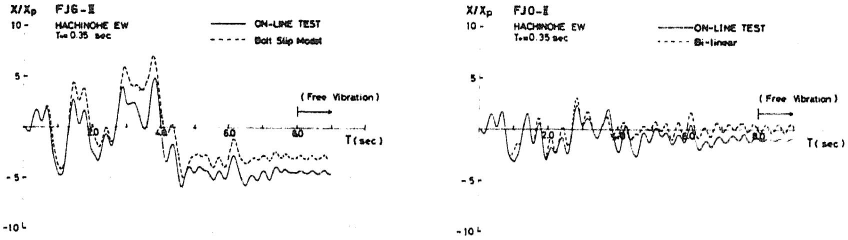


Fig.6 Time histories of response displacements

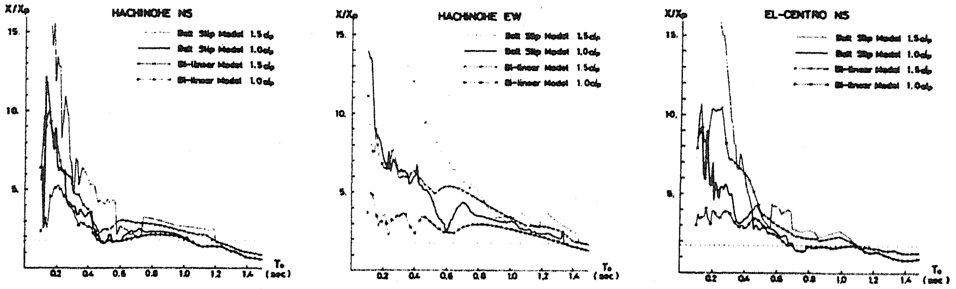


Fig.7 Maximum displacement spectra

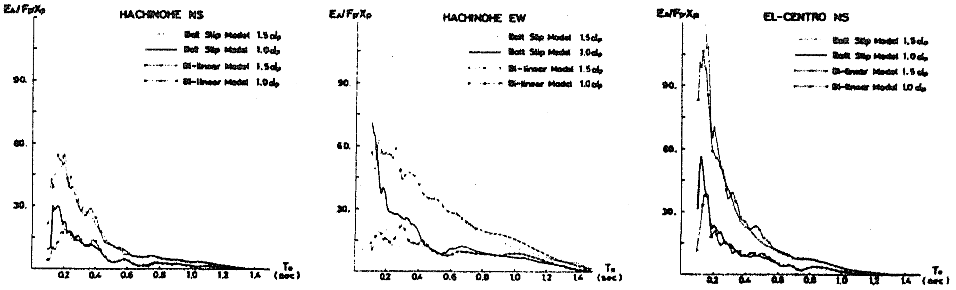


Fig.8 Abrorbed plastic strain energy spectra