INELASTIC ANALYSIS OF EARTHQUAKE RESPONSES OF SINGLE-STORY FACTORY BUILDINGS TAKING ACCOUNT OF TORSIONAL VIBRATION

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SUMMARY

Research work in connection with this paper includes inelastic analysis of earthquake responses of single-story factory buildings, whose roofs continue to act as wholesome units under seismic shock. The each roof of unequal-height multi-span single-story building is taken to be a rigid disc with its mass concentrated at its centre of gravity. According to this model a computer program was developed for the investigation of inelastic earthquake responses of single-story factory buildings subjected to ground motion in one or two directions.

INTRODUCTION

Reinforced concrete single-story factory buildings are very common in China. Such single-story buildings were severely damaged during the Tangshan Earthquake of July, 28, 1976. Single-story factory buildings generally are assemblages of prefabricated columns, roof beams and slabs (Fig.1). Damages occurred in the connections as well as in the prefabricated elements. We can briefly summarize the damages experienced by these single-story buildings as follows:

(1) Owing to the weak connections between roof slabs and trusses, the slabs fell down one by one under strong seismic shock. This may even lead to collapse of the trusses and the upper part of columns.

(2) Though the roof systems continue to act as wholesome units under seismic action, horizontal cracks appeared at parts of the columns above footings or at the interfaces of upper and lower parts of columns, sometimes the X-type cracks also occured at the webs of I-columns.

(3) Along the longitudinal directions of factory buildings subjected to seismic load, compression members of bracing systems lost stability or the embedded steels connected with bracings were pulled out from the column concrete.

(4) Owing to the weak connections between the columns and walls, the longitudinal brick walls or the gable collapsed under seismic action.

Except the first one, all the above-mentioned damages may be analysed by the following computational model: In case the building is made up of spans with roofs at different levels, because the roof systems continue to act as wholesome units, then roof system at each level is taken to be a rigid disc with its mass concentrated at its centre of gravity (Fig.2). For every mass there are three degrees of freedom (two translational and one rotational). A bi-linear model is used for the restoring force.

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The equations of motion under earthquake excitation are as follows:

$$
\begin{bmatrix} [M_1] & & & & \\ & [M_2] & & & \\ & & \cdots & & \\ & & & [M_r] & \\ & & & \cdots & \\ & & & & [M_n] \end{bmatrix}
\begin{Bmatrix} \{\ddot{\delta}_1\} \\ \{\ddot{\delta}_2\} \\ \cdots \\ \{\ddot{\delta}_r\} \\ \cdots \\ \{\ddot{\delta}_n\} \end{Bmatrix}
+
\begin{bmatrix} [C_{11}][C_{12}] & & & \\ [C_{21}][C_{22}][C_{23}] & & & \\ \cdots\cdots & & & \\ & [C_{r,r-1}][C_{r,r}][C_{r,r+1}] & & \\ & \cdots\cdots & & \\ & & & [C_{n,n-1}][C_{n,n}] \end{bmatrix}
\begin{Bmatrix} \{\dot{\delta}_1\} \\ \{\dot{\delta}_2\} \\ \cdots \\ \{\dot{\delta}\} \\ \cdots \\ \{\dot{\delta}\} \end{Bmatrix}
$$

$$
+
\begin{bmatrix} [K_{11}][K_{12}] & & & \\ [K_{21}][K_{22}][K_{23}] & & & \\ \cdots\cdots & & & \\ & [K_{r,r-1}][K_{r,r}][K_{r,r+1}] & & \\ & \cdots\cdots & & \\ & & & [K_{n,n-1}][K_{n,n}] \end{bmatrix}
\begin{Bmatrix} \{\delta_1\} \\ \{\delta_2\} \\ \cdots \\ \{\delta_r\} \\ \cdots \\ \{\delta_n\} \end{Bmatrix}
= -
\begin{bmatrix} [M_1] & & & & \\ & [M_2] & & & \\ & & \cdots & & \\ & & & [M_r] & \\ & & & \cdots & \\ & & & & [M_n] \end{bmatrix}
\begin{Bmatrix} \{\ddot{\delta}_g\} \\ \{\ddot{\delta}_g\} \\ \cdots \\ \{\ddot{\delta}_g\} \\ \cdots \\ \{\ddot{\delta}_g\} \end{Bmatrix}
$$

COMPUTER PROGRAM

A computer program was developed for the analysis of inelastic earthquake responses of single-story multi-span factory buildings. In setting up the stiffness matrix of whole structure, it is necessary to go through the following steps:

(1) An intermediate column which is taken to be a typical member (Fig. 3) is divided into four elements. According to double component - model the stiffness coefficients corresponding to the elastic or the plastic state must be given to the stiffness matrix of elements.

(2) The matrices of the unit elements are assembled to form the matrix of the single column. The reactions per unit displacement at joint 2 and joint 4 (Fig. 3) are solved by displacement method. These reactions are the stiffness coefficients of the single column.

(3) The stiffness coefficients of the single columns will be summarized one by one along the longitudinal direction of building and will be assembled to form the stiffness matrix of the whole structure.

BRIEF SURVEY OF WORKED EXAMPLES OF TYPICAL SINGLE-STORY FACTORY BUILDINGS

In order to study the elastic and inelastic earthquake responses of single-story factory buildings we selected two typical buildings for examples. One is a single-span and the another is a building with two spans of unequal heights. Besides, both buildings have gable walls only at one end.

The plan and the transverse section of the single-span building are shown in Fig. 4. The stiffness coefficient of the single bent is equal to 116 t/m, the stiffness coefficients of gable and longitudinal wall with bracings are equal to 14000 t/m. The mass and moment of inertia of roof system including the upper parts of walls are equal to 89.79 t-sec^2 /m and 53335.7 t-sec^2 -m, respectively. The yielding displacement at the top of the column is 0.037m. After the column entered into the plastic state, the corresponding stiffness coefficient is equal to 10% initial value.

The plan and the transverse section of the other buildings are shown in Fig.5. The dimensions of cross sections for all columns are: for the upper parts 40 x 40 cm and for the lower parts 40 x 70 cm. All the masses (M_1 and M_2) are 89.79 t-sec^2/m and the moments of inertia corresponding to M_1 and M_2 are 61955.5 t-sec^2-m. The stiffness coefficients of gable and longitudinal walls with bracings are same as those for the single-span building. The yielding moments of the columns of this two-span building at section 0 and 2 (See Fig.3) are equal to 40 and 10 t-m respectively.

The damping ratio is taken to be 5% for two examples.

We adopted four kinds of actual records of earthquake ground motion: Tianjin 1976 (aftershock), El-Centro 1940 N-S and W-E, Haicheng 1975 (aftershock) and used them as input data.

ELASTIC EARTHQUAKE RESPONSES OF SINGLE-STORY FACTORY BUILDINGS

Single-Span Building When the Tianjin, El-Centro 1940 N-S and Haicheng accelerograms with equal peak values (134 gal) were respectively inputed into the single-span building, the elastic earthquake responses of Fig.6 were obtained. It is necessary to point out that owing to the rotational action of the roof system, the displacements of column, along the longitudinal direction had different values. Fig. 6 only shows the translational component at the centre of gravity of the building. It means that the displacement far from the gable end were of larger value and that at the gable end approached to zero. Likewise, the Fig. 7 and Fig. 9 to Fig. 14 also show the displacement at the centre of gravity only.

From Fig. 6 it can be found that the displacement responses to Tianjin accelerogram is much stronger than those to Haicheng accelerogram. The long period components predominate in Tianjin accelerogram and the short period components predominate in Haicheng. For single-story factory buildings with long natural periods (near 1 sec) resonance can be easily excited by the Tianjin accelerogram. This phenomenon agrees with the damages in Tianjin areas.

Unequal height Building When the Tianjin accelerogram was inputted into the unequal-height building (Fig. 5) the elastic displacement responses (Fig. 7) and moment responses of Fig. 8 were obtained. From Fig. 8 it can be found that the high vibration mode of the building greatly increased the moment at the interface of the upper and lower parts of the intermediate column and caused large cracks at such positions. This phenomenon also agrees with the damages in Tianjin areas.

INELASTIC EARTHQUAKE RESPONSES OF SINGLE-STORY FACTORY BUILDINGS

Single-Span Building with Symmetrical Stiffnesses in Longitudinal Direction ($k_{yl} = k_{ym}$). During vibration of the single-story factory building, the column far from the gable end experienced large displacements. Of course, these columns entered into plastic state earlier than others. The inelastic earthquake responses to Tianjin and El-Centro 1940 N-S accelerograms with equal peak values (134 gal) are shown in Fig. 9 and

Fig. 10, respectively. Evidently, the inelastic maximum displacement responses are less than the elastic and the building always vibrated at one side. For the single-span building subjected to ground motion in two directions (input data* : El-Centro 1940 N-S, W-E) the displacement response in X-direction is shown in Fig. 11.

Single-Span Building with Unsymmetrical Stiffnesses in Longitudinal Direction ($k_{y1} \neq k_{ym}$). A building with unsymmetrical stiffnesses in longitudinal direction is encountered with when:

(a) the original structure is unsymmetrical;

(b) under seismic action the longitudinal wall collapses or the bracings yield at one side.

If we assume k_{y1} = 14000 t/m and k_{ym} = 7000 t/m, the inelastic displacement response to El-Centro 1940 N-S is shown in Fig. 12. Fig. 12 shows different responses between the two buildings with symmetrical and unsymmetrical stiffnesses of longitudinal walls. For the single-span building subjected to ground motion in two direction (input data* : El-Centro 1940 N-S, W-E) and if one side of longitudinal wall was allowed greatly to decrease in stiffness, the inelastic displacement responses are shown in Fig. 13 (Compare with Fig. 11). The difference between unsymmetrical and symmetrical is very evident.

Unequal-Height Single-Story Factory Building The inelastic displacement responses to Tianjin accelerogram for unequal-height single-story building are shown in Fig. 14, which includes the following cases:

(a) Plastic hinge appeared only at joint 1 (See Fig. 5);

(b) Plastic hinge appeared only at joint O (See Fig. 5).

From Fig. 14a it can be found that owing to the fact that the upper parts of columns entered into plastic state, the displacement responses became strong (Compare with Fig. 7). Besides, from Fig. 14b it can be found that relative motions between the two masses were very evident, and easily caused the upper parts of intermediate columns to enter into the plastic state.

CONCLUSION

(1) In the aseismic design of single-story factory buildings the effects of torsional vibration in the plane of roof system can not be neglected. This is particularly true for buildings having gables at one end only, because in such cases, the columns far from the gable end undergo large displacements under seismic action which may cause severe damages.

(2) Because the natural periods of single-story factory buildings are near the predominate period of ground motion in Tianjin area, resonance of such buildings may be easily excited by the earthquakes in Tianjin area. The calculated results in this paper agree with the damages observed in Tianjin area.

(3) For unequal-height single-story factory buildings, owing to the relative strong motions between two masses, the bottom sections of the upper parts of intermediate columns are critical sections and damages usually take place at such regions. The calculated results which are shown in Fig. 14b can also explain the above mentioned phenomenon.

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* In order to compare with the responses to Tianjin accelerogram, the peak values of El-Centro 1940 N-S, W-E accelerograms were reduced to 134 gal.

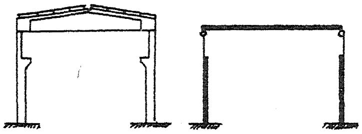


Fig.1 Single-story factory building

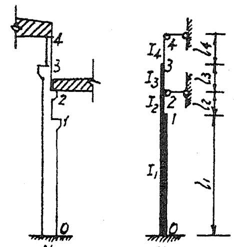


Fig.3 Intermediate column of building

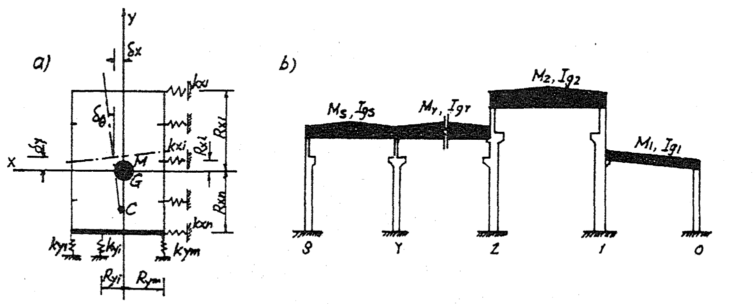


Fig.2 Single-story factory building: a) single-span; b) unequal-height multi-span.

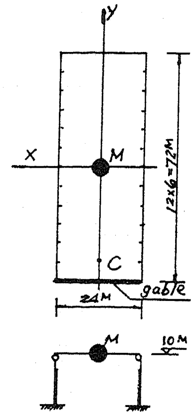


Fig.4 Plan and transverse section of single-span building

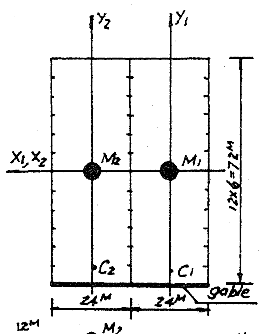


Fig.5 Plan and transverse section of unequal-height two span building

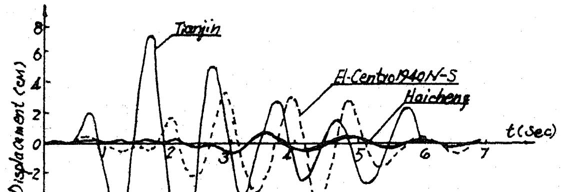


Fig.6 Displacement response historles of single-span building

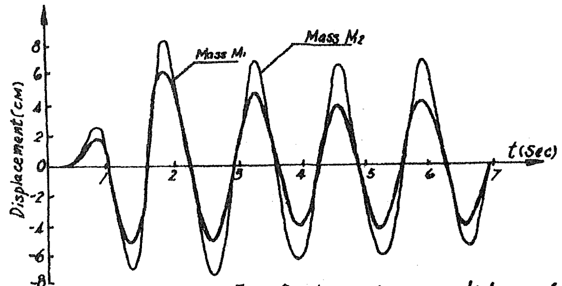


Fig.7 Displacement response histories of unequal-height two-span building

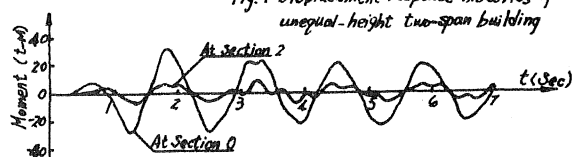


Fig.8 Moment response histories of intermediate column

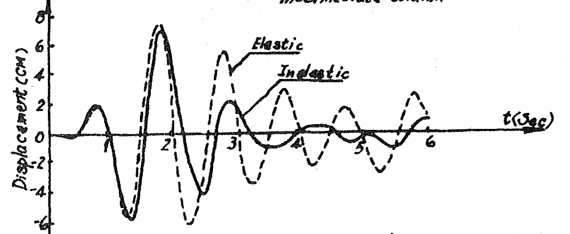


Fig.9 Displacement response histories of single-span building

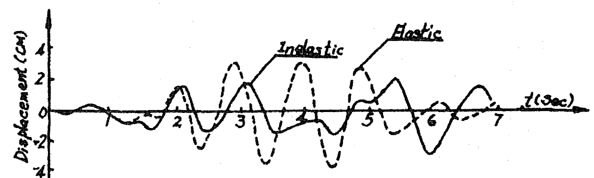


Fig.10 Displacement response histories of single-span building

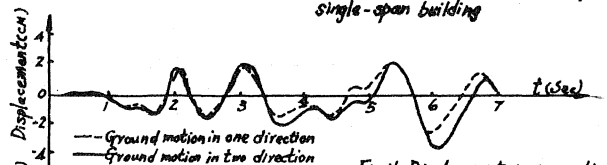


Fig.11 Displacement response histories of single-span building in X-direction

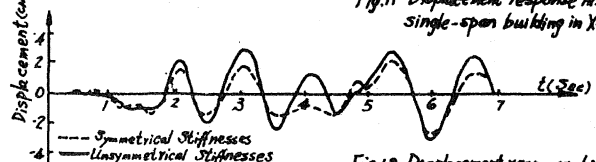


Fig.12 Displacement response histories of single-span building in X-direction

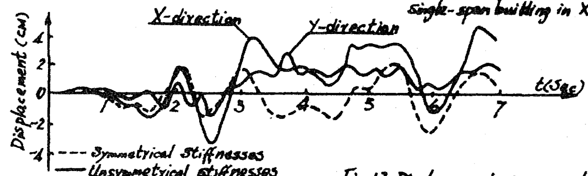


Fig.13 Displacement response histories of single-span building

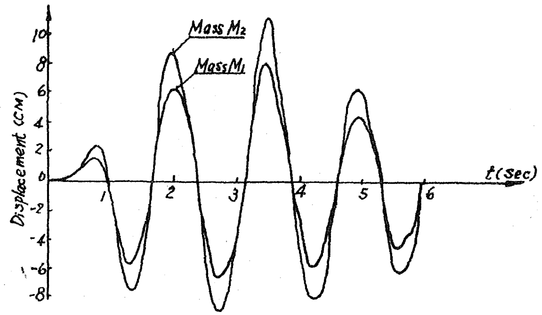


Fig. 14a Displacement response histories of unequal-height two-span building (Plastic hinges appeared only at joint 1 - See Fig. 5)

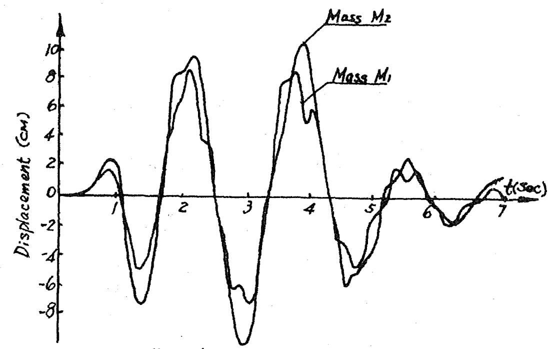
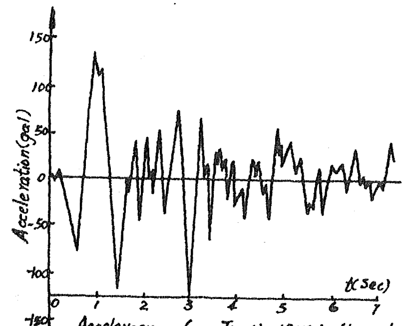
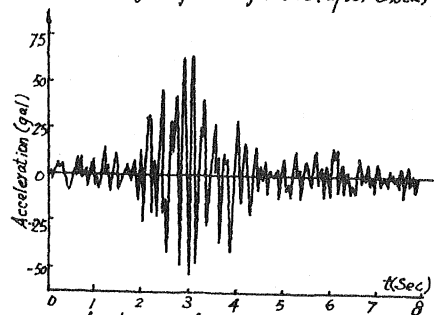


Fig. 14b Displacement response histories of unequal-height two-span building (Plastic hinges appeared only at joint 0 - See Fig. 5)



Acceleyogram from Tianjin 1976 (after shock)



Accelerogram from Haicheng 1975 (after shock)