# Studying seismic behavior of mixed structures in height

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**SUMMARY:**

In this paper, irregularity is investigated in structures with non-uniform distribution of stiffness and mass in vertical direction. These structures consist of two parts: the lower part is usually made of concrete and the upper part of steel. The analysis of these structures is complicated and code-based design has many problems for them. Here, the seismic behavior of mixed structures are studied while they have reinforced concrete frames with shear walls in lower stories and steel frames with bracing in upper stories. For this purpose, first, the buildings with different numbers of concrete and steel stories are designed. Then their overstrength, ductility and response modification factors are calculated under earthquake loads, using OpenSees software. In this regard, static push over analysis, nonlinear dynamic analysis and incremental dynamic analysis (IDA) have been performed. Then seismic parameters such as period and response modification factor are obtained and used in regression analysis in order to achieve the proper formula. Finally, two formulas, effective in designing such buildings, are presented for these parameters.

*Keywords: mixed structure, response modification factor, transition story*

## 1. INTRODUCTION

Mixed structures are the buildings with different types of materials at their stories. The lower parts of these buildings are usually made of concrete and their upper parts of steel. Such structures have been widely used in multi-story buildings. Constructing a steel structure on existing concrete building is ordinary and generates mixed structures. This structural system has non-uniform stiffness, mass, material and damping in vertical direction. Up to now, no comprehensive research has been conducted on the performance of these structures and their seismic response under a real earthquake. Response modification factor is one of the most important parameters against earthquake forces. This factor is related to the ability of structure to dissipate earthquake energy with its nonlinear deformation without collapse. Seismic codes provide no seismic provisions, particular response modification factor and period for mixed structures and just a few suggestions have been mentioned there. Common types of mixed structures are reinforced concrete frames with shear walls in lower stories and steel frames with bracing in upper stories. In this paper the seismic behavior of such structures with one transition story has been studied. The transition story, located in the transition level, is a composite (steel-concrete) story with composite columns, shear walls and steel bracing. Response modification factor of mixed structures with different numbers of steel and concrete stories has been determined.

## 2. STRUCTURAL CONFIGURATION AND MATERIAL

Five structures with different numbers of steel and concrete stories are designed and shown in Table 2.1. In this table, the names of structures have been listed in abbreviated forms. For example, "2S1T2C" stand for a building with two steel stories (S), one transition story (T) and two concrete stories (C). Table 2.2. shows the specifications of materials used for the design and analysis of these buildings.

**Table 2.1.** Modeled buildings

| Number of stories | Building Name | Number of steel stories | Number of transition stories | Number of concrete stories |
|---|---|---|---|---|
| 5 | 0S0T5C | 0 | 0 | 5 |
| | 1S1T3C | 1 | 1 | 3 |
| | 2S1T2C | 2 | 1 | 2 |
| | 3S1T1C | 3 | 1 | 1 |
| | 5S0T0C | 5 | 0 | 0 |

**Table 2.2.** Specifications of materials

| Concrete material C35 | | steel material ST37 | |
|---|---|---|---|
| Mass per unit volume | $2.5\ {}^{gr}/_{cm^3}$ | Mass per unit volume | $7.848\ {}^{gr}/_{cm^3}$ |
| Modulus elasticity of concrete $E_c$ | $2.5e5\ {}^{kg}/_{cm^2}$ | Modulus elasticity of steel $E_s$ | $2.1E6\ {}^{kg}/_{cm^2}$ |
| Compressive strength of concrete $F_c$ | $350\ {}^{kg}/_{cm^2}$ | Yield stress of steel $F_y$ | $2400\ {}^{kg}/_{cm^2}$ |
| Yield stress of longitudinal bars $F_y$ | $4000\ {}^{kg}/_{cm^2}$ | Ultimate stress of steel $F_u$ | $3700\ {}^{kg}/_{cm^2}$ |
| Yield stress of transverse bars $F_{ys}$ | $3000\ {}^{kg}/_{cm^2}$ | | |

For all buildings, the story height is 3m, and the total height is 15m. The plan and facade of a building, as a sample, are shown in Figs. 2.1. and 2.2., respectively.

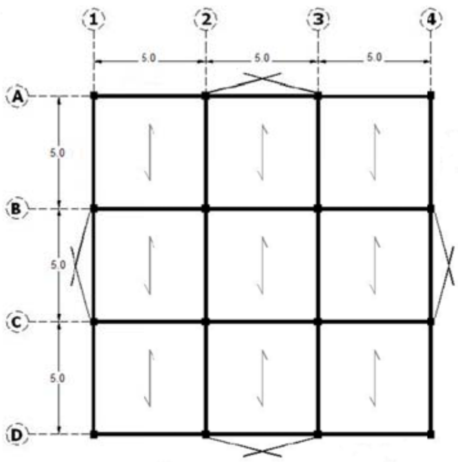


**Figure 2.1**. Plan of the building (unit: m)

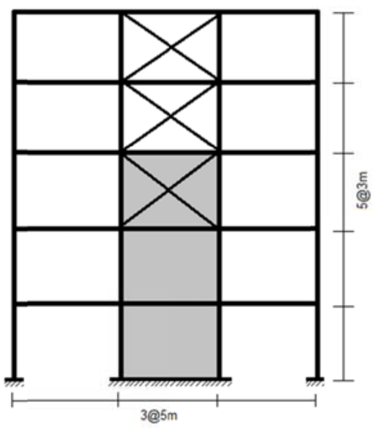


**Figure 2.2.** Facade of the building (unit: m)

The structures were loaded by Iranian code of practice for seismic resistant design of buildings, standard No. 2800 3rd edition. It is supposed that all structures have been constructed on type II of soil classification in the standard 2800 [1]. The nominal values of dead load and live load on slabs of steel stories are 7.0kN/m$^2$ and 2.0kN/m$^2$, respectively, and on slabs of concrete stories 10.5kN/m$^2$ and 5.0kN/m$^2$, respectively. According to standard No. 2800 in mixed structures, the value of R (response modification factor) used in the design of lower system should not be greater than that of upper system. Two procedures, discussed in the following, are used for designing mixed structures. Is case of satisfying the below mentioned conditions, both procedures can be used, otherwise only the first one is applied for designing mixed structures.

The conditions are:

1) Both parts are classified separately as regular structure.
2) The average story stiffness of lower part is at least 10 times greater than that of upper part.
3) The fundamental period of entire structure is not greater than 1.1 times the period of upper part, while this part is considered as a separate structure with fixed base.

Procedure 1:

In this procedure, the seismic load is determined based on the lower R factor in the height of structure. The empirical formula, resulted in the lower fundamental period, is used for two systems.

Procedure 2:

This procedure has two stages:

a) The upper flexible part is designed as a separate structure with rigid supports based on the R factor corresponding to its structural system.
b) The rigid lower part is designed as a separate structure, using its corresponding R factor. The reactions between upper and lower part is increased by ratio of R factor of upper part to the R factor of lower part and super-imposed to the loads acting on the lower portion.

The R factor of upper stories should be equal or less than that of lower stories, according to standard No. 2800. Therefore, intermediate concrete moment resistant frame with intermediate reinforced concrete shear wall (R=8) is used in the lower stories and a dual system composed of special moment resistant frame and concentric bracing (R=9) in the upper stories. In Procedure 1, mixed structures should be designed based on the lowest R of lateral force resisting system. Therefore, the entire mixed structure is designed using response modification factor 8 [1]. Fundamental periods of all buildings are calculated using Eqn. 2.1. [1]:

$$T=0.05H^{3/4} \tag{2.1}$$

where, H is the height of building in meters, measured from the base level [1]. Steel and concrete stories are designed according to the codes AISC-ASD89 and ACI 318-99, respectively.

## 3. MATHEMATICAL MODELS

2D frames of designed buildings are modeled and analyzed in OpenSees software, a sample of which is shown in Fig.3. While all other connections are rigid in the upper structure, the braces are connected to the frame by hinge joint. The 0.001 imperfection of length is considered at the middle of these members in order to model the buckling of steel columns and bracings. Shear wall element is placed between two mid columns in the lower concrete stories, Fig.3. Two rigid beams are modeled above and under this element. In the transition story, steel brace is placed in the shear wall by which it is prevented from buckling. By the way, imperfection is not considered. In the transition story, shear wall is modeled as two elements and

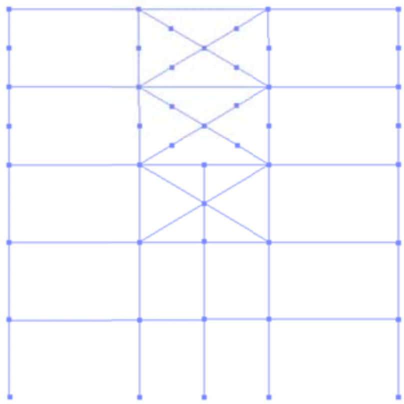

**Figure 3**. Mathematical model

attached to the center of bracing in its middle joint in order to model the interaction between shear wall and bracings. The transition story columns are composite and consist of a steel box placed in a square section of concrete. The beam over composite columns is steel. Uniaxial bilinear hysteretic material is used for steel elements. Nonlinear beam-column element is adopted for steel columns and X-bracing, and displacement-based beam-column element for beams [2]. Corotational coordinate transformation is considered for all elements and zero-length element is used in modeling the hinge connection (bracing to steel frame). Concrete 02 material is used for concrete columns and beams. Confined Mander model is used to consider concrete confinement [3]. Another displacement-based beam-column element is used for shear wall. In this research the ratio of mass of concrete stories to mass of steel stories is approximately 1.5.

## 4. RESPONSE MODIFICATION FACTOR

Response modification factor is calculated based on Uang method.

Uang, using ideal capacity curve, has indicated that response modification factor consists of the following parameters [4]:

1) Ductility Reduction Factor

Buildings have the capacity of dissipating energy caused by their ductility, because of which elastic design force ($V_e$) is reduced to yield strength level ($V_y$ ). Therefore, ductility reduction factor is defined as follows:

$$R_\mu = V_e / V_y \qquad (4.1)$$

2) Overstrength factor

Overstrength factor is calculated through dividing idealized yield strength by the first significant yield strength ($V_s$):

$$R_s = V_y / V_s \qquad (4.2)$$

3) Allowable stress factor

Allowable stress factor is the ratio of first significant yield strength to the allowable stress design strength and here is considered as 1.44.

$$Y = V_s / V_w \quad (4.3)$$

The above three components are expressed as follows in calculation of response modification factor (R):

$$R = R_m . R_s . Y \quad (4.4)$$

Like any other parameter, the above equation can be redefined as:

$$R = (V_e / V_y).(V_y / V_s).(V_s / V_w) = V_e / V_w \quad (4.5)$$

where, $V_e$ is elastic response strength, $V_y$ is idealized yield strength; $V_s$ is first significant yield strength; $V_w$ is allowable stress design strength. The allowable stress factor (Y) becomes unity when structure is designed by ultimate strength method and the response modification factor is reduced to:

$$R = R_m . R_s = V_e / V_s \quad (4.6)$$

## 5. SEISMIC PERFORMANCE ANALYSIS

### 5.1. Modal analysis

The first two periods of the five structures are tabulated in Table 5.1.

**Table 5.1.** First two periods of the structures

| Structure | ETABS | | OpenSees | |
|---|---|---|---|---|
| | $T_1$ (sec) | $T_2$ (sec) | $T_1$ (sec) | $T_2$ (sec) |
| 0S0T5C | 0.288 | 0.109 | 0.244 | 0.094 |
| 1S1T3C | 0.292 | 0.148 | 0.264 | 0.125 |
| 2S1T2C | 0.374 | 0.274 | 0.312 | 0.246 |
| 3S1T1C | 0.416 | 0.269 | 0.378 | 0.245 |
| 5S0T0C | 0.591 | 0.351 | 0.578 | 0.346 |

### 5.2. Damping Ratio

The damping ratios are considered as 5% and 2% for concrete and steel structures, respectively. The equivalent damping ratio of mixed structure is calculated based on the studies of Papageorgiou et al [5]. To obtain the damping ratio of mixed structure, the modal mass and period ratio of upper structure to lower structure are calculated and the equivalent damping ratio is estimated [5]. The values of first and second mode frequencies, damping ratios and Rayleigh damping coefficients (α and β) are presented in Table 5.2.

**Table 5.2.** Damping ratios

| Structure | $\omega_1$(Rad/Sec) | $\omega_2$(Rad/Sec) | ξ | α | β |
|---|---|---|---|---|---|
| 0S0T5C | 25.75076 | 65.44985 | 5% | 1.847996 | 0.001096 |
| 1S1T3C | 23.79994 | 50.26548 | 4.6% | 1.485998 | 0.001242 |

| | | | | | |
|---|---|---|---|---|---|
| 2S1T2C | 20.13841 | 49.4739 | 3.1% | 0.887375 | 0.000891 |
| 3S1T1C | 16.62218 | 49.0873 | 2.4% | 0.546364 | 0.00067 |
| 5S0C | 10.90074 | 31.63739 | 2% | 0.324293 | 0.00094 |

### 5.3. Pushover Analysis

Nonlinear static analysis is done and pushover curves are plotted by OpenSees software. According to Fig. 5.1., by increasing the number of steel stories in the mixed structures, their stiffness and lateral load-carrying capacity decrease. In the complete steel structure, the first nonlinear behavior is appeared when X- bracing is buckled in the third story of complete steel structure.

In the mixed structure and also concrete building, the first plastic hinges are formed in the shear walls of the first stories. The first significant yield strength is determined from pushover analysis and presented in Table 5.4.

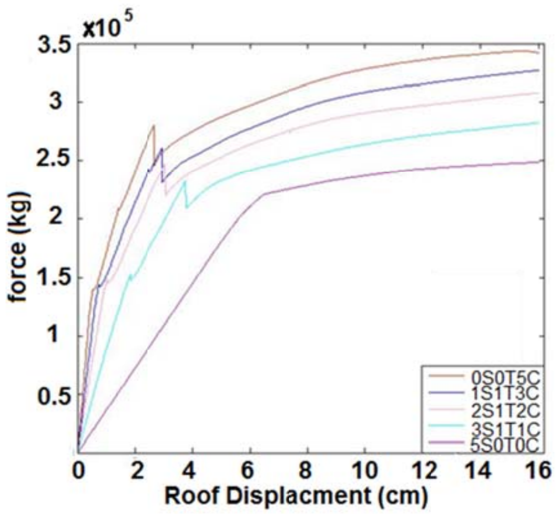


**Figure 5.1.** Pushover Analysis curve

### 5.4. IDA Analysis

Ten earthquake records, registered on soil type II, are used for IDA analysis and tabulated in Table 5.3. These records are selected based on their PGAs, causative earthquake magnitude and their epicentral distances. IDA analyses have been carried out on the mentioned records and damping ratios. IDA curves are plotted, Figs. 5.2. to 5.6., using maximum interstory drift ratio of the building as damage measure (DM) and spectral acceleration at the first-mode period as intensity measure (IM). The latter is scaled by Hunt and Fill tracing algorithm.

**Table 5.3.** Ground motion records used in IDA analysis

| Record Number | Record Name | Station | Soil Type | Date | PGA(g) |
|---|---|---|---|---|---|
| 1 | Chi-Chi, Taiwan | CHY080 | II | 9/20/1999 | 0.902 |
| 2 | Coyote Lake | Gilroy Array 3 | II | 8/6/1979 | 0.434 |
| 3 | Kobe | KJMA | II | 1/16/1995 | 0.821 |
| 4 | Landers | Coolwater | II | 6/28/1992 | 0.417 |
| 5 | Loma Prieta | Corralitos | II | 10/18/1989 | 0.644 |
| 6 | Morgan Hill | Anderson Dam | II | 4/24/1984 | 0.423 |
| 7 | N. Palm Springs | N. Palm Springs | II | 7/8/1986 | 0.694 |
| 8 | Northridge | Santa Monica | II | 1/17/1994 | 0.883 |
| 9 | Bam | Bam | II | 26/12/2003 | 0.767 |
| 10 | Tabas | 9101 Tabas | II | 9/16/1978 | 0.917 |

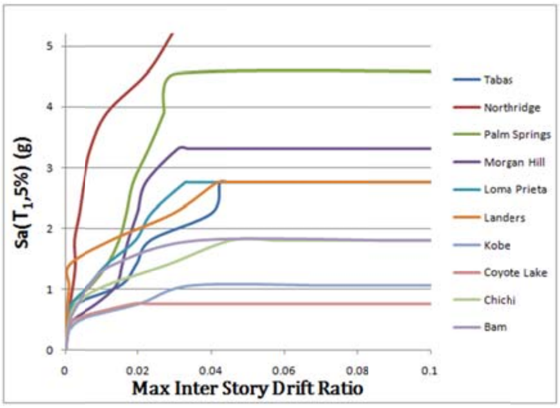


**Figure 5.2.** IDA curves of 0S0T5C building

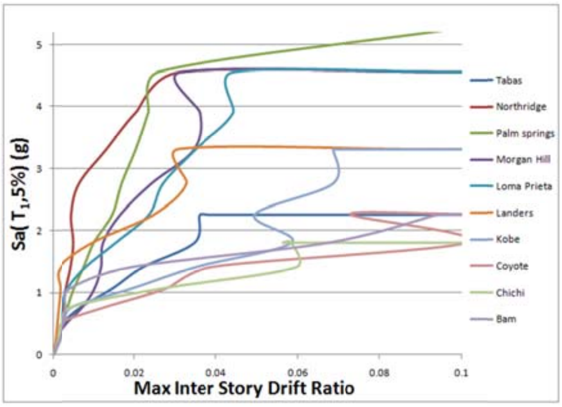


**Figure 5.3.** IDA curves of 1S1T3C building

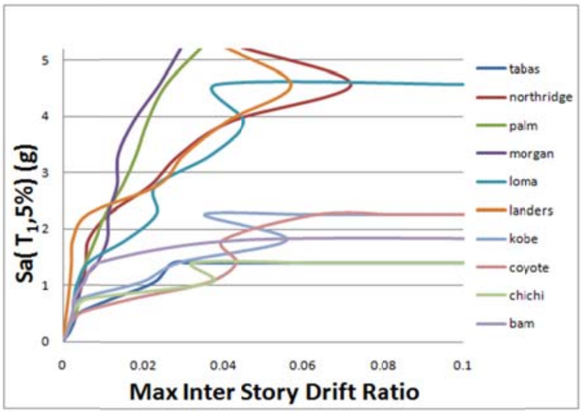


**Figure 5.4.** IDA curves of 2S1T2C building

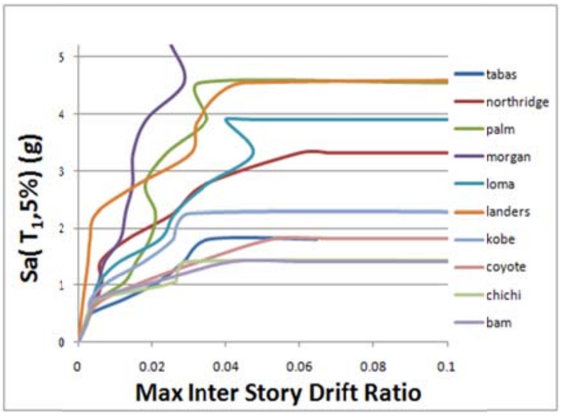


**Figure 5.5.** IDA curves of 1S1T3C building

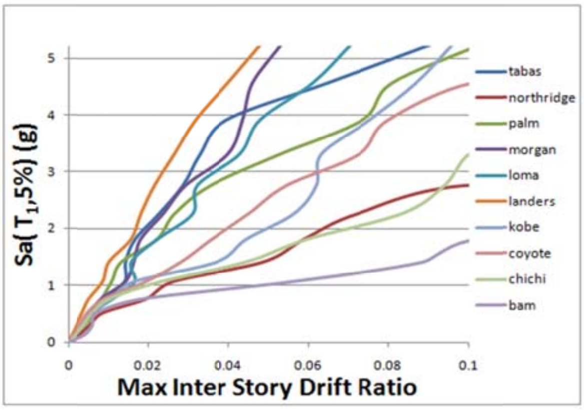


**Figure. 5.6.** IDA curves of 5S0T0C building

According to standard NO. 2800, for buildings with fundamental period of less than 0.7second, the maximum interstory drift ratio is 0.025 [1] caused by the base shear ($V_y$). $V_s$is obtained from pushover analysis, and $V_y$ and $V_e$ from IDA analysis. The values of response modification factor and period of structures are given in Table 5.4.

**Table 5.4.** Response modification factors

| Name | $T_1$ (sec) | DM (MaxDrift) | $V_s$(kgf) | $V_y$(kgf) | $V_e$(kgf) | $R_s$ | $R_\mu$ | R(LRFD) | R(ASD) |
|---|---|---|---|---|---|---|---|---|---|
| 5S0T0C | 0.578 | 0.025 | 202036 | 298464.7 | 978217 | 1.47 | 4.84 | 7.16 | 10.31 |
| 3S1T1C | 0.378 | 0.025 | 210265 | 297234.9 | 1242819.5 | 1.41 | 4.19 | 5.91 | 8.51 |
| 2S1T2C | 0.312 | 0.025 | 220205 | 317900.2 | 1386754.4 | 1.44 | 4.36 | 6.29 | 9.07 |
| 1S1T3C | 0.264 | 0.025 | 234496 | 328533.1 | 1446735.8 | 1.40 | 4.39 | 6.16 | 8.88 |
| 0S0T5C | 0.244 | 0.025 | 252717 | 338171.3 | 1575442.7 | 1.33 | 4.67 | 6.23 | 8.97 |

## 6. CONCLUSIONS

According to the results obtained in this research:

1. By increasing the number of concrete stories in the mixed structures, period is reduced, and stiffness, first significant yield strength ($V_s$) and idealized yield strength ($V_y$) increase.
2. Despite the existence of non-uniform stiffness, mass, material and damping in vertical direction of mixed structures, they have appropriate seismic behaviors. The values of response modification factors of mixed structures are approximately close to those of similar concrete structure.
3. A formula is proposed for response modification factor based on the results obtained here for the mentioned factor as follows:
   For Allowable Stress Design (ASD):

$$R_{ASD}(n_1,n_2) = -0.545n_1 - 0.589n_2 + 12.478 \quad (6.1)$$

For Limit State Design (LSD):

$$R_{LRFD}\,(n_1,n_2) = -\,0.378n_1 - 0.409n_2 + 8.665 \quad (6.2)$$

4. A formula is proposed for the first period of five story building as:

$$T_1(n_1,n_2) = 0.08n_1 + 0.128n_2 - 0.144 \quad (6.3)$$

where, $n_1$ is the number of steel stories and $n_2$ is the number of concrete stories with one transition story.

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