Understanding Secondary Damages due to Non- Structural Elements in High-rise Buildings

by

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in

*New Technologies for Urban Safety of Mega Cities in Asia* (USMCA2016)

Report No: IIIT/TR/2016/-1

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Hyderabad - 500 032, INDIA
November 2016
Understanding Secondary Damages due to Non-Structural Elements in High-rise Buildings

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ABSTRACT

In the present scenario of building construction world-wide, there is a significant increase in the cost percentage of non-structural elements compared to overall building cost. However, in some cases during past earthquakes, where the main structure suffered minimal damage, it was noticed that there were severe problems in the functionality of building and also sometimes leading to injuries & life loss. It is observed that significant percentage of population is injured due to overturning of objects such as furniture. This problem is attributed mainly to the behavior of non-structural elements which are not designed taking into account their seismic performance.

The aim of this study is to analyze the behavior of a rigid body i.e. a NSE, particularly the toppling behavior under the action of seismic forces. A linearized solution for the dynamic equation of motion of the rigid body is obtained. The results are obtained in the form of angle of rotation of body against time, providing limits of safety of the NSE against toppling under applied seismic loading. A transformer has been modelled to illustrate the same. Also a tool has been generated using python scripts to graphically simulate the behavior of nonstructural elements under earthquake loading, by placing NSEs in different floors. This tool helps us in identifying whether the NSE will slide, rock or topple when subjected to certain seismic loading and provides the limits of safety for the same.

Keywords: secondary damages, nonstructural elements, high-rise buildings, topple, seismic loading.

1. INTRODUCTION

State of art review (Roberto Villaverde, 1997) describes secondary structures as those systems and elements that are housed or attached to the floors, roof, and walls of a building or industrial facility that are not part of the main or intended load bearing structural system for the building or industrial facility, but may also be subjected to large seismic forces and
must depend on their own structural characteristics to resist these forces. This review also classifies these secondary structures into three broad categories: (1) Architectural components; (2) mechanical and electrical equipment; and (3) building contents. A nonstructural element can be either anchored or unanchored but the current work focuses only on unanchored ones. Since these nonstructural elements (NSEs) are not a part of the main load-resisting system of any building, these are often neglected from the design point of view. Performance in the past earthquakes clearly pointed out that the inadequacy of design provisions for non-structural elements and their attachments has resulted in poor performance of several buildings despite of their proper structural design. Such experiences from earthquakes has shown that the failure of equipment, and the debris caused by falling objects and overturned furniture, may also critically affect the performance of vital facilities such as fire and police stations, emergency command centers, communication facilities, power stations, water supply and treatment plants and hospitals. A most unfortunate case among such cases is the death of a student, who, during the 1987 Whittier Narrows earthquake in California, was struck by a falling precast panel while walking out of a parking structure (Taly, 1988).

Finally, with regard to the economic impact caused by the failure of nonstructural components, evidence from earthquakes has repeatedly shown that; failure of architectural, mechanical or electrical elements and contents can cause extreme economical losses [Miranda and Taghavi, 2003].

A great deal of research effort has been devoted over the past 30 years to the development of rational methods for the seismic analysis of these secondary structures. Furniture inside a building, an important museum art craft, or any object that overturns during an earthquake can be assumed as a rigid block, therefore is very important to analyze the behavior of this object under a dynamic force (M. Chiriatti, G. P. Cimellaro, 2012). The motion of a non-anchored body can be defined under in 6 basic conditions: rest, slide, rock, slide-rock, free flight and impact. These motions have been analyzed by various authors. Housner (1963) analyses the rocking motion of structures of inverted pendulum type under action of a seismic load assuming them to be slender and provides a solution for the minimum acceleration amplitude of a half-sine pulse that is needed to overturn a rigid block. Later Nicos Makris et. al (1998) proved that the above solution is not conservative and proposes an approximate solution.

Unlike previous literatures which assumed NSE to be slender, this work analyses the rocking and toppling behavior of a rigid body without any assumption of slenderness. Polynomial solution has been proposed and the behavior has been modelled using python scripts.

2. EARTHQUAKE BEHAVIOR OF NON STRUCTURAL ELEMENTS

The inertia force induced in a nonstructural element during random shaking may cause it to either slide, rock or topple if it is unanchored in vertical or lateral direction or if the anchor fails. A rigid block is said to be sliding if the base of the NSE is horizontally translating on that surface, overcoming friction. Similarly rocking means that the NSE is not sliding (translating) but lifts off from heal while locked at the toe. Toppling is nothing but rocking NSE losing its balance and finally ending up sideways on the surface on which it is rested. The motion may also be a combination of sliding and rocking, but this work does not discuss the combined motion. The possibility of occurrence of above discussed
motions depends upon both the intensity of shaking of surface on which it is placed and the geometry of the NSE. Using these parameters the conditions can be derived to know whether the block will slide, rock or topple.

2.1 Conditions for NSE to slide, rock or topple

Consider a rigid block (figure 1) of height $2h$ and base dimension (along the direction of loading) $2b$. Let $m$ be the mass of the nonstructural element considered and $W$ denote its weight. Assuming the acceleration $a_{eq}$ is shaking the floor on which the NSE is placed due to the applied seismic load. This acceleration induces an inertial force, $F_{eq}$ (equal to the product of mass of the block and acceleration $a_{eq}$) and an overturning moment $M_e$ about its toe (equal to the product of above induced force, $F_{eq}$ and the height, $h$ of the NSE).

\[ F_{eq} = ma_{eq} \quad (1) \]
\[ M_e = F_{eq}h \quad (2) \]
\[ F_f = \mu mg \quad (3) \]
\[ M_o = mgb \quad (4) \]

In addition to these moments and forces, the self-weight creates a restoring moment ($M_o$) about its toe with a magnitude equal to the product of weight $W$ and width $b$ of the block. Also owing to this self-weight, a frictional force ($F_f$) of $\mu mg$ opposing the motion is generated, where $\mu$ is the coefficient of static friction. Now using these equations, conditions to determine the motion of the NSE under given vibrations were obtained.

2.1.1 Static

For an NSE to remain static under given vibrations the net force and the net moment acting on it should be zero. That is, induced force should not exceed frictional force and overturning moment should be balanced by restoring moment due to its weight. Upon equating these forces and moments, the following equations can be obtained for the static case:

\[ a_{eq} < \mu g \quad \text{And} \quad a_{eq} < \frac{bg}{h} \quad (5) \]

2.1.2 Sliding

Sliding is nothing but the translation of the block without any angular displacement. Therefore for an NSE to only slide, the restoring moment should balance the overturning moment but the friction force should not nullify the applied induced force. On applying these conditions, the equations that should be satisfied for sliding to take place were:

\[ a_{eq} > \mu g \quad \text{And} \quad a_{eq} < \frac{bg}{h} \quad (6) \]

2.1.3 Rocking

Rocking of an NSE is its rotation about its toe without any translation. For this to occur the induced force should be balanced by the friction whereas the overturning moment should
exceed the restoring moment. On applying these conditions, the equations that should be satisfied for a nonstructural element to rock were:

\[ a_{eq} < \mu g \quad \text{And} \quad a_{eq} > b g / h \]  

(7)

2.1.4 Toppling

Toppling of the rigid body usually occurs if the line of action of the self-weight crosses its toe. But under the dynamic conditions, it is possible for an object to return back i.e. rock, instead of toppling if momentarily, the line of action of self-weight crosses the toe. Therefore it is not possible to directly write any conditions as such. In order to understand the toppling behavior of NSE, one needs to formulate its dynamic equation of motion under applied loading and find the angular displacement. Hence, the dynamic equations of motion which are available in literature are reproduced below [e.g., Yim et al, 1980].

3. DYNAMIC EQUATION OF MOTION OF NSE

Assuming that the above considered block has rotated through an angle \( \theta \) at the time \( t \) from initial condition, on balancing the moments about the toe of the NSE, equation of motion of the block can be written as

\[ I_o \ddot{\theta} + m g R \sin(-\alpha - \theta) = -ma_{eq} R \cos(-\alpha - \theta), \quad \theta < 0 \]  

(8.a)

\[ I_o \ddot{\theta} + m g R \sin(\alpha - \theta) = -ma_{eq} R \cos(\alpha - \theta), \quad \theta > 0 \]  

(8.b)

Where \( I_o \) is the moment of inertia.

4. PROPOSED SOLUTION

\[1\] R denotes the half of diagonal length of the block i.e. \( R = \sqrt{h^2 + b^2} \), \( \alpha = \tan^{-1} b / h \)
Shaking of ground during any seismic activity takes place in the order of seconds. Since $t$ is small, the angular displacement $\theta$ can be assumed as a polynomial function of time. Here in this work it has been assumed as a polynomial of degree 3.

$$\theta = a + bt + ct^2 + dt^3$$  \hspace{1cm} (9)

where the variables $a$, $b$, $c$ and $d$ were obtained by substituting this polynomial $\theta$ and the initial conditions in the above dynamic equation of motion.

$$I_o(a + bt + ct^2 + dt^3) + mgR \sin(-\alpha - (a + bt + ct^2 + dt^3)) = -ma_eq R \cos(-\alpha - (a + bt + ct^2 + dt^3)), \quad \theta < 0 \hspace{1cm} (10.a)$$

$$I_o(a + bt + ct^2 + dt^3) + mgR \sin(\alpha - (a + bt + ct^2 + dt^3)) = -mR a_eq \cos(\alpha - (a + bt + ct^2 + dt^3)), \quad \theta > 0 \hspace{1cm} (10.b)$$

Since an earthquake signal can be written in the terms of sine and cosines, initially a sinusoidal loading is considered to be acting on the NSE.

$$a_eq = a_o \sin \omega t \hspace{1cm} (11)$$

The complexity of above equation (10.a) was reduced by expanding sine and cosine terms into polynomial terms using Taylor$^2$ series expansions. Finally, equation gets reduced to

$$I_o(2c + 6dt) + mgR[( -\alpha - (a + bt + ct^2 + dt^3)) - \left(\frac{(-\alpha-(a+bt+ct^2+dt^3))^3}{3!}\right) + \cdots] =$$

$$-mR[(\omega t)^3 - \frac{3!}{3!} + \cdots][1 - \left(\frac{(-\alpha-(a+bt+ct^2+dt^3))^2}{2!}\right) + \cdots], \quad \theta < 0 \hspace{1cm} (12)$$

By applying the initial displacement of the NSE as $\theta(0) = \theta_0$ and equating the coefficients, the unknown parameters were derived. The initial velocity of the block is assumed to be zero.

The final solution for the dynamic equation of motion of a rigid body is hence being proposed as

$$\theta(t) = \alpha - \varepsilon, \quad \text{if } \theta > 0$$

$$\theta(t) = -\alpha - \varepsilon, \quad \text{if } \theta < 0$$

Where,

$$\varepsilon = a + bt + ct^2 + dt^3$$

---

$^2 \sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} \cdots, \quad -\infty < x < \infty \quad \cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} + \cdots, \quad -\infty < x < \infty$
\[a = \alpha - \theta_0\]
\[b = 0\]
\[c = \frac{(a - \frac{a^3}{6} + \frac{a^5}{120} - \frac{a^7}{5040})P}{2}\]
\[d = \frac{Qw(1 - \frac{a^2}{2} + \frac{a^4}{24} - \frac{a^6}{720})}{6}\]
\[P = \frac{3g}{4R}\]
\[Q = \frac{3a_o}{4R}\]

The above solution was derived when the loading is sinusoidal in nature. But actual seismic load is a random but periodic function and hence can be reduced into combinations of sine and cosine terms using Fourier transformation. For every frequency in the Fourier transform of the input earthquake load, the angular displacement is calculated using above discussed equations. And the summations of all these displacements result in the actual final displacement of the NSE. An NSE topples if this angular displacement exceeds 90 degrees which is nothing but the failure of NSE.

5. CASE STUDY: RESPONSE OF ELECTRICAL EQUIPMENT UNDER SEISMIC LOADING

Past earthquakes experienced high damage of electrical equipment such as transformers due to overturning failure. Limits of failure of such objects can be easily derived by considering them as rigid blocks. This study considers an electrical transformer with a base dimension of 0.5m (along the direction of force) and a height of 1.5m which has been subjected to El Centro (1944) (figure 3) ground motion. The PGA of input ground motion is 0.29\(g\) at time \(t = 2.16\ \text{sec}\). Assumed the coefficient of static friction \((\mu)\) is 0.45.

On substituting in equations (6) and (7), it can be seen that the block rocks but does not slide. Since the block is rocking, the whole time history of angular displacement of the block has been derived using proposed solution as in equation (13) which is shown in figure (2).
From the above result, figure (2) it is observed that the considered transformer overturns at time $t = 0.24$ secs.

6. CASE STUDY: RESPONSE OF NSEs PLACED ON A BUILDING UNDER EARTHQUAKE LOADING

Using the above proposed procedure, a G+3 storey building with 5 different NSEs on each of the typical floor was modelled graphically using python scripts. The building is subjected to El Centro (1944) ground motion and the acceleration response at each floor is calculated using Central Difference Method (CDM). The seismic properties of the building considered and the acceleration responses at each floor are mentioned below (Table 1 and 2).

Table 1: Properties of considered building and block

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumped mass at each typical floor</td>
<td>$2.38 \times 10^6$ kg</td>
</tr>
<tr>
<td>Lumped mass at each terrace</td>
<td>$1.96 \times 10^6$ kg</td>
</tr>
<tr>
<td>Storey height</td>
<td>3 m</td>
</tr>
<tr>
<td>Stiffness of all floors</td>
<td>$1.78 \times 10^9$ N/m</td>
</tr>
</tbody>
</table>

Table 2: Maximum ground motion and maximum floor acceleration obtained from CDM

<table>
<thead>
<tr>
<th>Floor</th>
<th>Maximum acceleration(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.17</td>
</tr>
<tr>
<td>II</td>
<td>0.19</td>
</tr>
<tr>
<td>III</td>
<td>0.22</td>
</tr>
<tr>
<td>IV</td>
<td>0.28</td>
</tr>
</tbody>
</table>
The different NSEs considered in this study are Refrigerator, washing machine, study table, squat table and closet. All these objects are arranged as shown below (figure 4). Geometrical properties of the considered NSEs are shown in table (3). A coefficient of friction of 0.4 is considered for refrigerator and washing machine whereas it is considered as 0.19 for two wooden tables. For the closet it is considered to be 0.3. The response of NSE placed on the above building is represented below (table 4). It has been observed that under ground shaking, the refrigerator placed on the bottom two stories are safe whereas the one on third floor undergoes rocking motion and finally topples after 0.38 seconds. Washing machines are safe in all the floors but both the tables slide on second and third stories of course with different amplitudes. Closets placed at third and second floors rock, finally toppling after 0.4 seconds while the one on first floor remains static.

<table>
<thead>
<tr>
<th>NSE</th>
<th>Breadth b (m)</th>
<th>Depth/Width d (m)</th>
<th>Height h (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigerator</td>
<td>0.42</td>
<td>0.6</td>
<td>1.85</td>
</tr>
<tr>
<td>Washing Machine</td>
<td>0.4</td>
<td>0.6</td>
<td>0.85</td>
</tr>
<tr>
<td>Study Table</td>
<td>0.9</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Almarah/Closet</td>
<td>0.3</td>
<td>0.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Squat Table</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 3: Applied El Centro ground motion - acceleration \((m/s^2)\) in time (sec) and frequency (Hz) domain
6. CONCLUSION

In order to correlate the amount of loss with the failure of nonstructural elements, a comprehensive method to numerically calculate the limits of failure of nonstructural elements is required. In order to achieve this, a complete understanding of the behavior of NSEs under the action of seismic loading is essential. This paper proposes a method to numerically model the rocking behavior of an NSE and came up with the limits of overturning failure. The same was illustrated using an electrical transformer. Also the behavior of different NSEs placed at various floors of a building, subject to earthquake loading has been graphically modelled.
REFERENCES