On the Vulnerability of Coastal Buildings in the Gulf of Cadiz under Tsunami Forces

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Abstract

This paper aims at evaluating the behavior of the first row reinforced concrete (RC) buildings next to the shore in the Morocco under the threat of tsunami waves.
Previous research studies developed the generation, propagation and inundation of such destructive waves, and proposed some building fragility curves using statistical results from previous tsunami surveys, multi-criteria models and a buildings classification matrix. This paper aims to establish reasonable fragility curves by analyzing the engineering parameters of RC structure. For this purpose, we use in this study various norms recommendations and the results of numerical finite element modeling using a reliable software.

**Keywords**: Tsunami, coastal buildings, masonry, RC buildings, fragility curves

1. **Introduction**

Tsunami events have produced enormous catastrophes on coastal cities. The tsunamis of December 2004 Indian Ocean and the March 2011 Tohoku-Oki were devastators to the structures near the coast. This raises enormous questions on the resistance of buildings along different coastal areas in many countries threatened by tsunami waves, such as in the Gulf of Cadiz, which has been subject to the impact of the 1 November 1755 Lisbon earthquake (El Mrabet [8], Baptista & al [4], Kaabouben et al. [11]). Recently, countries bounded by the Gulf of Cadiz, i.e. Morocco and Portugal have launched and worked on many research projects (Astarte & Inspired) in order to determine the resilience of coastal cities, whether from a human vulnerabilities perspective or from the resistance of structures. In order to bring this later point of view to light, investigating the behavior of buildings near the shore and fully struck by a probable tsunami attack is a necessity.

Different research studies proposed some qualitative models to evaluate the fragility of buildings. The PTVA and PTVA2 models (Papathoma tsunami vulnerability assessment) were widely used (Papathoma et al. [6]). In some test cities test in the Gulf of Cadiz such as Tangier, the assessment of vulnerability of this city was assessed using geographic information system (GIS-based) approaches, based on a multi-criteria model (Benchekroune et al. [5], Omira et al. [14]). Other attempts were done in cities of Rabat and Salé with the proposition of a building classification matrix (Atillah et al. [3]). All of these studies use statistical assessment data collected from previous tsunami events, and classification matrix techniques.

Focusing more on the building element, other studies developed reflexes about a pushover-like model (Foytong and Ruangrassamee [19]). Others have analyzed the problem by treating most of the building elements hit by the tsunami wave, and describing their limits of resistance and behavior of plastification.

In a similar way, we set in this paper to establish the fragility curves by using basically real time structure analysis tools. We study the mechanical movement of structures from a civil engineering view. We use the recommendations of buildings
codes and simulate the reaction of an RC building with a finite element software. Finally, we propose fragility curves and compare them to previous tsunami surveys.

2. Briefing methods and norms recommendations

2.1 Vulnerability of masonry walls

For an RC structure type, which is the most common type of buildings constructed nowadays in Morocco, the infill masonry has an important role to fulfil. This URM (Unreinforced masonry) is used for its sonic and thermic protection, but also important for their stiffness because it increases the capacity of the whole building. Hence, many previous and recent researches have studied infill walls of masonry and have advanced different models that describe well its behavior (G. Milani [13], M. Puglisi et al. [17], G.N. Pande et al. [16]).

Walls of masonry are non-structural elements of the usual RC building. Two types of walls are to be considered: out of plane and in plane walls.

2.1.1 Out of plane walls

The out of plane walls are too weak against the lateral loads applied normally to their surface, and that is due to the geometrical inertia property and to the weak combination of the masonry elements (brick and mortar) to each other. Generally, the enormous types of bricks and mortar joints which are made from different elements (clay, sand, etc.) under different percentages and fabrication conditions, make the deal hard enough to handle so as to its complex behavior because it’s a composite material (Zucchi et al. [22]). To solve this problem, norms such as the EUROCODE’6 describe some characteristics of the masonry and recommend applying a security coefficient.

For our study, we have adopted the EUROCODE’6 norm to evaluate the vulnerability of an out of plane wall. For average walls not expanded in its height or length, the vertical moment expression is by:

\[ M_{ed2} = \alpha_2 \times W_{ed} \times l^2 \]

The horizontal moment is given by:

\[ M_{ed1} = \alpha_1 \times W_{ed} \times l^2 = \mu \times M_{ed2} \]

Where \( W_{ed} \) is the lateral force per unit of surface, \( l \) is the length of the wall and \( \alpha_1 \) and \( \alpha_2 \) are coefficients that depend of the links to the adjacent frame. These moments have to be inferior to the resistant moment \( M_{rd} = f_{xd} \times t^2/6 \) where \( f_{xd} \) is the flexion resistance of the masonry wall, given by the norm and \( t \) is the thickness of the wall.

In order to evaluate the tsunami impact on coastal buildings next to the shore, we have adopted the Fema’646 recommendations. Though researches are still not
well developed to determine the exact behavior of tsunami wave due to its complexity, the Fema’646 norm gives an approximation of tsunami forces values, based on theoretical calculations and on experts estimations. The forces of tsunami are:

- Hydrostatic forces;
- Hydrodynamic forces;
- Impulsive forces;
- Buoyant forces;
- Debris impact forces;
- Debris damming forces;
- Uplift forces; and
- Additional gravity loads from retained water on elevated floors.

In this study, we start by the analysis of the ground floor. We have focused on the main three first forces (Yeh, [12]) considering that the buoyant forces are neglected (water does not reach the first floor’s slab) and debris action is significantly uncertain. These forces are given by:

- Hydrostatic forces: \( F_h = \rho_s \times g \times \left( h_{\text{max}} - \frac{h_w}{2} \right) b h_w \) where \( \rho_s \) is the fluid density including sediment (1200 kg/m\(^3\) = 2.33 slugs/ft\(^3\)), \( g \) is the gravitational acceleration, \( b \) is the breadth (width) of the wall, \( h_w \) is the water height and \( h_{\text{max}} \) is maximum water height above the base of the wall at the structure location.

- Hydrodynamic forces: \( F_d = \frac{1}{2} \rho_s \times C_d \times B (hu^2)_{\text{max}} \) where \( C_d \) is the drag coefficient, \( B \) is the breadth of the structure in the plane normal to the direction of flow (i.e. the breadth in the direction parallel to the shore). Note that the hydrodynamic forces must be based on the parameter \( (hu^2)_{\text{max}} \), which is the maximum momentum flux per unit mass occurring at the site at any time during the tsunami, roughly estimated by
  \[
  (hu^2)_{\text{max}} = gR^2 (0.125 - 0.235 \frac{Z}{R} + 0.11 \left( \frac{Z}{R} \right)^2 )
  \]
- Impulsive forces: \( F_s = 1.5F_d \)

2.1.2 In plane walls

Many research studies have analyzed infill masonry walls under a seismic shear force oriented in the wall plane direction. Predicting the behavior of these infill walls, which are composite materials, is established through three major models. The first is the microscopic level, where the elemental matrix is constituted with a unit of bricks and adjacent mortar. The second considers a mesoscopic level, where the elementary unit is a simple layer of consecutive brick-mortar (joints) system that can be reproduced vertically to give the wall its height. Finally, the macroscopic level where the wall is considered as a plate, with a hypothesis of a good and valid homogenization transformation.
Mainestone (1970) has worked on the macro-model and suggested a replacement of the shear wall by an equivalent diagonal struts (fig (1)) with geometrical parameters (Fema306) as follows:

\[
\frac{W}{d} = 0.175\lambda_h^{-0.4}
\]

where \( d \) is the length of the strut frame and \( \lambda_h = h_{col} \sqrt[4]{\frac{E_{inf}t_{inf}\sin(2\theta)}{4EI_{inf}}} \), where \( h_{col} \) = column height between centerlines of beams; \( E_{inf} \) = modulus of elasticity of the masonry panel; \( EI \) = flexural rigidity of the columns; \( t_{inf} \) = thickness of the infill panel and equivalent strut; \( h_{inf} \) = height of infill panel; and \( \theta \) = angle, whose tangent is the infill height-to-length aspect ratio, \( \theta = \tan^{-1}\left(\frac{h_{inf}}{L_{inf}}\right) \) in which \( L_{inf} \) = length of infill panel.

In fact, the results of such a “replacement” are very similar to the labs results (Evaluating Strength and Stiffness of Unreinforced Masonry Infill Structures US ARMY, [1]). The principle of this method is the assumption of the one degree of freedom of the structure where the floor mass is dominant. For the tsunami, this condition is not verified because the distribution of the forces is uniform or triangular and it is applied directly to the column, not to the floor mass.

2.2 Vulnerability of an RC building frame

In our study, the determination of vulnerability of RC buildings constructed next to the shore is modelled through a finite element analysis to determine the building reaction. An RC building model is presented as follow to illustrate the analysis.
To make different possible scenarios of the building’s behavior, we have taken values of 4, 5 and 6m ground floor (GF) height, then two floors above of a typical 2.8m height each. The infill masonry walls are not taken into account, considering the worst scenario of the collapse of all the masonry walls. In fact, we are interested to analyze the behavior of the structural elements that support the building. In addition, the software calculate the frame design under the ultimate, working and seismic loads with recommended combinations in the Eurocodes norms.

The forces mentioned previously are applied to the columns row-by-row. The distribution of the hydrodynamic force is considered uniform, and the hydrostatic one is triangular (Fema 646). The equation of movement is given by (Eq1):

\[ M\ddot{U} + C\dot{U} + KU = P(t) \]  

(1)

Where M is the mass matrix, C is the damping matrix, K is the rigidity matrix and P is the input forces matrix. U is the instantaneous displacement vector.

Eq1 is transformed to the simplified form (Eq2):

\[ m_j(\ddot{y}_j + 2\xi_j\omega_j\dot{y}_j + \omega^2_jy_j) = p_j(t) \]  

(2)

Where \( U(t) = \sum_{j=1}^{n} y_j(t)D_j \) and \( p_j(t) = D_j^TP(t) \) by applying the integral of Duhamel, we can have the temporal displacement (Eq3):

\[ y_j(t) = \frac{1}{m_j\omega_{Dj}} \int_0^t p_j(\tau)e^{-\xi_j\omega_j(t-\tau)} \sin[\omega_{Dj}(t-\tau)]d\tau \]  

(3)

\[ \omega_{Dj} = \omega_j\sqrt{1 - \xi_j^2} \]

Hence, the variation of these forces in time \( (P(t)) \) is given by the diagram in figure (2), which is based on laboratory results. (P. Lukkunaprasit & al, [12])

![Figure 2: time history of the loading forces of tsunami on the building](image)

3. Results

3.1 Masonry

The objective is to estimate the threshold of the wave height ($H_d$) from which we obtain the destruction of the infill masonry wall. We have taken the hypothesis that the wall is supported by its foundation and the two columns next to it. The local beach slope is 1/50 average (2%).

Some results are presented in fig (3): (t: the thickness of the wall, $z$: the elevation of the location of the building)

![Figure 3](image-url)

Figure 3: influence of the length (a), the height (b) and the thickness (c) of the URM wall loaded by hydrodynamic and hydrostatic forces

The more the wall’s length increases the more the failure height decreases, so the vulnerability of walls with larger lengths is higher. Otherwise, the more the wall’s height increases the more the failure height increases, so the vulnerability of higher walls is lesser. The vulnerability of walls with lesser thickness is considerable.

3.2 RC frame

Previous researches (Omira et al. [5], [14], tsunami methodology and results overview (UNISDR Global assessment report [21]) have worked on some developed numerical models of the propagation and inundation of tsunami on coastal areas in the Gulf of Cadiz. Their results show that the ground elevation at the maximum tsunami penetration measured from the initial shoreline in those areas of the Gulf of Cadiz is 5m average. So, based on these calculations and on the recommendations of FEMA646, we have got these values of forces (Table 1): (HS: Hydrostatic forces (triangular); HD: Hydrodynamic forces (uniform))
<table>
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<tr>
<th>Effective Height of inundation(m)</th>
<th>HS (KN) on the base/ml</th>
<th>HD(KN/m) uniform/ml</th>
<th>Surge(KN/m) uniform/ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.9</td>
<td>1.55</td>
<td>2.3</td>
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<tr>
<td>1</td>
<td>2.65</td>
<td>2.2</td>
<td>3.3</td>
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<td>4.45</td>
<td>2.85</td>
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<td>6.2</td>
<td>3.5</td>
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<tr>
<td>4.5</td>
<td>15</td>
<td>6.72</td>
<td>10.1</td>
</tr>
</tbody>
</table>

Table 1: max values of HS, HD and surge forces

By applying an approximated time history analysis, temporal variation of maximum displacements of the frame is illustrated in figure (4). The temporal oscillations of maximum displacement (fig (5)) show a good correlation between the analysis results with the results of lab experiment shown earlier (fig (2)). The envelope of maximum displacements of the first floor is shown in figure (6). Columns of the ground floor are under the combined flexion where the tsunami forces apply a bending moment in one hand and a vertical load applies a normal strain on the other hand. We make also the assumption that the building is still linked to the foundations (this case will be fully studied in other papers).

![Figure 4: temporal variation of displacement under the tsunami total force](image-url)
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Figure 5: temporal oscillations of max displacement

Figure 6: envelope of max displacements in the first floor (a and b) and Moments diagram (c). The movement is to the Y direction
In order to plot the curve of building capacity, we have extracted the maximum displacement from all the cases given by varying the inundation depth, the height of the ground floor (4m, 5m and 6m). We have also taken advantage from a reasonable comparison between the output results and the seismic analysis (RisK UE WP4 vulnerability of current buildings) to define correctly the two main points of the capacity curves the yield and ultimate points. Capacity curves are shown in figure (7).

![Capacity Curves](image)

**Figure 7: capacity curves (GF=ground floor)**

In order to plot fragility curves, we have used the procedure of RisK UE (LM2) where the spectral displacements are Sd1=0.7 Dy; Sd2=Dy; Sd3=0.5 Dy+0.25 Du; Sd4=Du (Dy is the displacement of the yield point and Du is displacement of the ultimate point ) and the parameters $\beta_1=0.25+0.07\ln(\mu_u)$; $\beta_2=0.2+0.18\ln(\mu_u)$; $\beta_3=0.1+0.4\ln(\mu_u)$; $\beta_4=0.15+0.5\ln(\mu_u)$ with $\mu_u=Du/Dy$

The obtained fragility curves are illustrated in figure (8). The cases of Sd1 and Sd2, which concern the non-structural elements of the ground floor (GF), are ignored because URM walls are destructed according to the first section results.
Figure 8: fragility curves for different cases
4. Interpretation

The fragility curves shown earlier present a detailed view of the vulnerability of RC type buildings. Calculated curves show a good approximation to the statistical damage curves (P(x5) and P(x6)) plotted with Japan tsunami’s survey for the same type of buildings (figure 9). The two types of curves show some acceptable correlation and give more accuracy to the previous statistical results from Japan tsunami (figure 8). However, we can assume that the statistical results are based widely on different types of buildings with multiple characteristics and material specifications. On the other hand, our model is still restricted to some limitations: study of ground floor only, three major forces and problems of scour and foundations. These studies will be fully investigated in the future.

5. Conclusion

Investigation of the vulnerability of coastal building due to a tsunami action is analyzed through the study of non-structural elements such as masonry walls. The out of plane forces are the main forces to act on the walls under hydrostatic and hydrodynamic forces. In addition, the frame resist by making movements of vibration to dissipate the energy induced by the hydrostatic, hydrodynamic and surge forces. Those forced oscillations behave according to the low of forced vibration. Capacity curves are then plotted and the fragility curves are produced. We find a good comparison between the Japan’s tsunami survey results [Suppasri et al. [20]] and our computed values is held. The utility of such procedure is rather
important because it is based only on analytical calculations and software modeling. The results can help improve the resilience from the tsunami phenomenon and should help to prevent the catastrophe of waste of lives and to be aware of the best ways of evacuation under such dangerous circumstances.

**References**


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