DAMAGE EVALUATION MODEL FOR STRUCTURAL ELEMENTS OF BLOCK CONCRETE BUILDINGS

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ABSTRACT

This study proposes a simplified methodology to estimate the damage level and reduction factor which shows the residual seismic capacity of reinforced concrete block elements from the maximum response calculated by methods such as pushover analysis, dynamic analysis and others. The methodology is based on simplified models to estimate the maximum residual crack width from the residual deformation related to flexural, shear and rotational components. The models are geometrical relations calibrated by using test data. The calculated crack width is used later to estimate the residual seismic capacity of the structural element. For this purpose, the necessary concept to evaluate the relations between the maximum residual crack width and the residual seismic capacity of structural elements is introduced in this study. This concept is necessary at the reconstruction stage after an earthquake and can be applied to assess the necessity of repairs and seismic retrofit for the damaged elements.

Keywords: Damage level, Residual crack width, Residual seismic capacity, Concrete block masonry.

1. INTRODUCTION

El Salvador is often affected by earthquakes due to its location on the border of two tectonic plates, the Cocos plate and Caribbean plate. The subduction process in the Pacific coast produces destructive earthquakes with magnitude higher than 7.0, which commonly bring a big damage along the country. Due to this reason and the seismic capacity of most Salvadorian structures, high damage concentrations are commonly observed in the affected area when an earthquake occurs.

In this country, the damage evaluation of structures has gained importance in recent years due to the lessons that past earthquakes have given. Following the experiences of the 1986 San Salvador and 2001 earthquakes, a guideline to quickly assess the global damage of buildings was developed (quick inspection guideline). Although a method for quick inspection has been already implemented, there is not a methodology to evaluate the damage state of structures either before or after an earthquake. This is an important issue to be addressed because the damage level evaluation is necessary to plan reconstruction strategies for the local authorities of the affected area. Pre-earthquake damage evaluation is used to study and evaluate the damage level of structural components by performing numerical analysis. This type of evaluation is strongly recommended to indirectly analyze repair costs, seismic capacity reductions and other aspects related to the damage levels of structural elements.

2. STRUCTURAL TEST

The studied specimens are concrete block walls which were built in accordance with the requirements of the Salvadorian Housing Code published in 1997 (Wall-A) and 2004 (Wall-B), respectively. The geometry and the vertical and horizontal reinforcement are presented in Figure 1. Additionally, the

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geometry and the reinforcement of the upper and foundation RC beam is also presented in Figure 1. The nominal width of both walls is 10cm and the width of the mortar joint between blocks is 1cm.

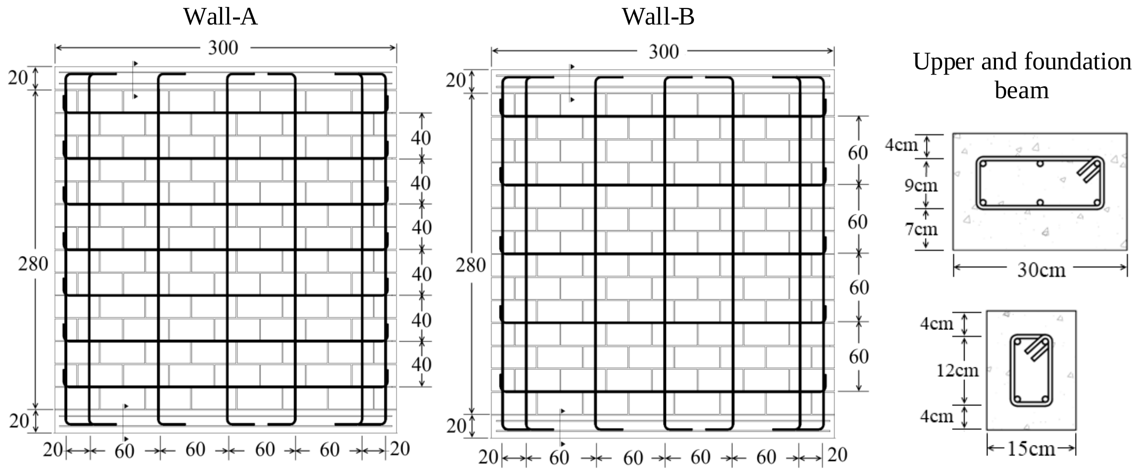

Figure 1. Geometry and arrangements of steel reinforcement for Wall-A and Wall-B (unit: cm)

The load application dispositive is composed by a hydraulic jack, which is able to provide a cyclical load applied parallel to the plane of the wall. The use of vertical loads in the tested walls is not considered because each tested specimen represents the wall of a Salvadorian one story house with a flexible roof system. Figure 2 shows the loading setup.

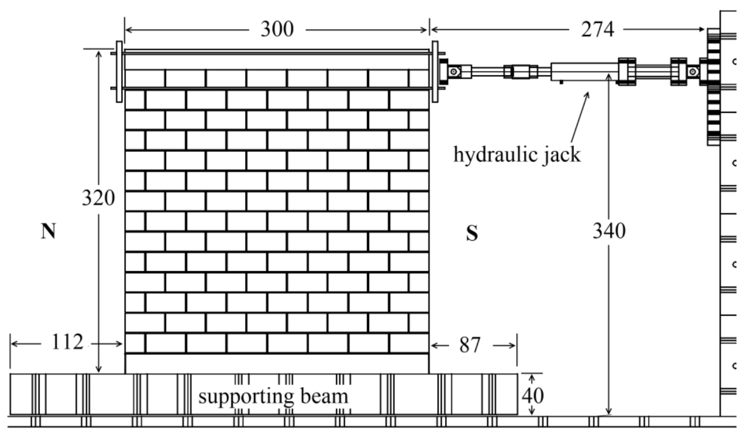

Figure 2. Loading setup (unit: cm)

3. METHODOLOGY OF DAMAGE EVALUATION MODEL

A simplified methodology to obtain the maximum residual crack width of a reinforced concrete block wall from numerical analyses is proposed. Hence, it is possible to relate the calculated crack width with the damage level and reduction of the seismic capacity of the damaged structural element.

The first step is to obtain the maximum response of the structural element under earthquake which can be estimated by methods such as pushover and dynamic analysis, for instance. Then, the residual displacement related to the maximum response is estimated by using the unloading stiffness.

In order to specify the dominant crack type, the next step is to decompose the residual deformation in to flexural, shear and rotational components. The amount of each deformation component is calculated by using the measured deformations of tested specimens.

Once each deformation component is obtained, the maximum residual crack width related to each component is estimated. For this purpose crack models based on geometrical relations which are calibrated by using test data are proposed.

Finally, the calculated maximum crack width can be associated with a damage level and the residual seismic capacity represented by the reduction factor η. Figure 3 shows a scheme of the procedure and required analysis in the proposed damage evaluation model.

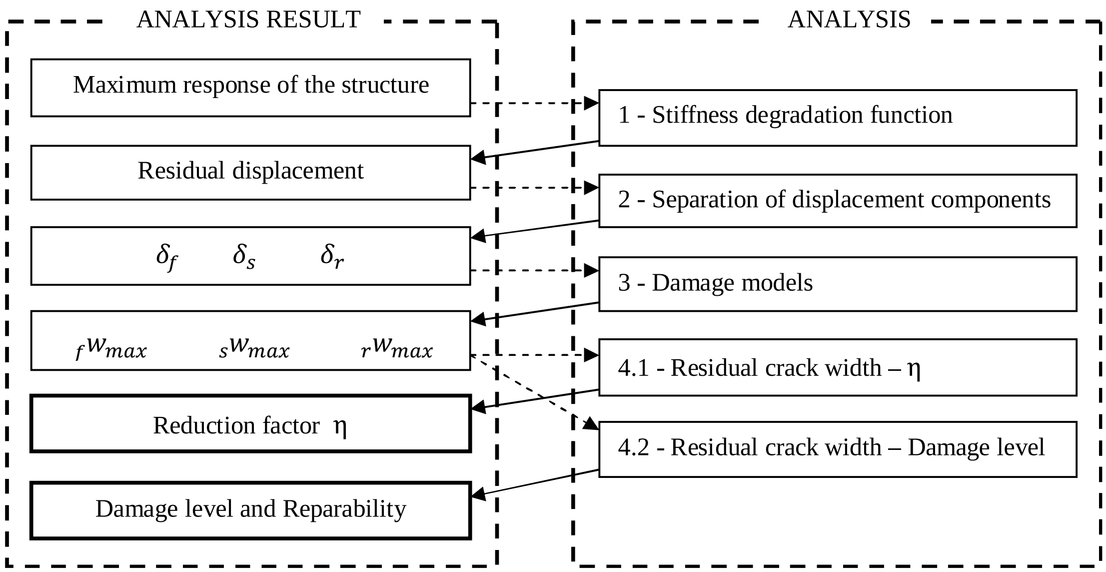

Figure 3. Procedure to evaluate the residual seismic capacity of block concrete wall

The reduction of the seismic capacity due to damage can be related to the residual hysteretic energy that the structure can dissipate during a new earthquake. In this sense, from the load-deformation curve obtained by the test of structural elements, the residual seismic capacity (E_R) is calculated as the difference between the original seismic capacity ($E_T = E_D + E_R$) and the dissipated energy (E_D). Figure 4 shows a scheme of this concept. (Maeda, 2009)

Conveniently, the reduction of the seismic capacity is represented as a reduction factor η of the initial seismic capacity E_T. This can be defined as the ration between the residual energy capacity and the original energy capacity (η=E_R/E_T).

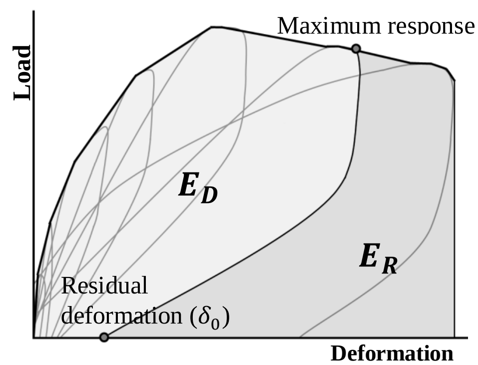

Figure 4. Determination of the residual seismic capacity (Maeda, 2009)

In order to consider the reduction of the seismic capacity in the proposed model, relationship between a reduction factor and the residual crack width is investigated.

4. RESULTS AND DISCUSSION

4.1 Calculation of the residual displacement from the maximum response of a structure

The unloading stiffness is necessary to determine, from a given maximum response, the displacement at unloading state (residual displacement).

In order to propose an unloading stiffness function for concrete block walls, the unloading stiffness of the tested models was calculated. Figure 5 shows the ratio between the yielding stiffness K_y and the unloading stiffness K_r for both specimens. A trend line of the results could be drawn in Figure 5 and represented by Eq.1.

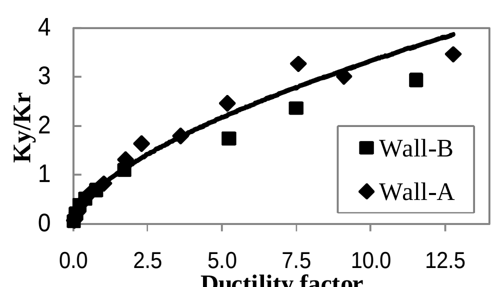

Figure 5. Ratio Unloading stiffness to yielding stiffness

$$\frac{K_y}{K_r} = 0.81\mu^{0.6} \quad (1)$$

Using Eq.1 it is possible to estimate the residual displacement as a function of the maximum response which is represented by the maximum displacement δ_{max} and lateral applied load P_{max} as follows:

$$\delta_0 = \delta_{max} - \frac{0.81\mu^{0.6}}{K_y}.P_{max} \quad (2)$$

4.2 Separation of deformation components

The amount of flexural δf, shear δs and rotational δr deformation component for Wall-A and Wall-B are presented in Table 1 and Table 2, respectively. The tables show the average values corresponding to the tendency presented by each deformation component. These values are considered from the first crack state to the yielding state (0.12% and 0.15% for Model A and B, respectively) and from the yielding drift angle to the ultimate state.

Table 1. Percentage of deformation components (Wall-A)

Drift angle (%)	δf/δt	δs/δt	δr/δt
0.04 to 0.18	0.68	0.26	0.05
0.18 to 0.4	0.55	0.24	0.20

Table 2. Percentage of deformation components (Wall-B)

Drift angle (%)	δf/δt	δs/δt	δr/δt
0.04 to 0.15	0.74	0.11	0.15
0.15 to 1.11	0.52	0.36	0.12

4.3 Models for crack evaluation of block concrete elements

The proposed models are developed to be applied in similar boundary and loading conditions to that used in the tested block concrete walls. For instance, as for the testing procedure, axial loads to simulate the weight of upper stories were not applied and the boundary condition of the top of the walls was unfixed (cantilever beam).

As for the model of flexural cracks, the cracking pattern shown in Figure 6 produces a flexural drift angle represented by Eq.3. The value x can be calculated as 52cm for displacement smaller than the yielding point and 21cm for larger displacements by section analysis.

$$\theta_f = \frac{\sum {}_f w_i}{b-x} \quad (3)$$

From the instrumental data, the variation of the longitude L_1 and L_2 is represented by ΔL_1 and ΔL_2, respectively (see Figure 6). Assuming $\Delta L_2 \approx 0$ and $\Delta L_1 \cong \sum {}_f w_i$ the following equation can be written:

$$\frac{\Delta L_1}{{}_f w_{max}} = k_f \quad (4)$$

k_f is the ratio between the sum of flexural crack width $\sum {}_f w_i$ and the maximum crack width ${}_f w_{max}$. This factor is used to relate the

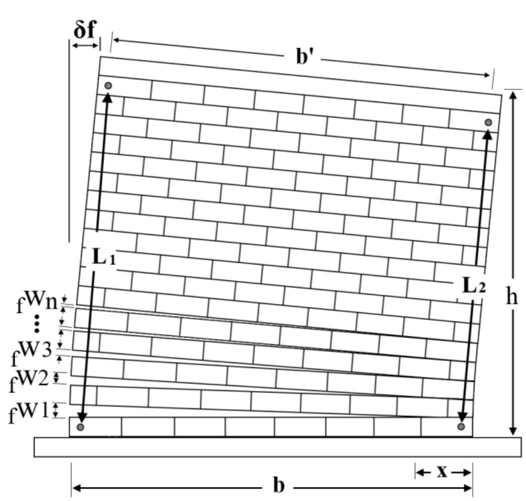

Figure 6. Flexural crack model

geometrical models and the instrumental data. Finally, Eq.5 is obtained from the system presented in Figure 6.

$$ {}_{f}w_{max} = \frac{\delta_f.(b-x)}{k_f.h'} \tag{5} $$

In the same way, a model for the maximum crack width due to the rocking effect is presented by Eq.6

$$ {}_{r}w_{max} = \frac{\delta_r.(b-x)}{h} \tag{6} $$

As for the shear cracks, the proposed model is based on the assumption that the horizontal shear deformation is produced by the sum of the horizontal component of the shear crack widths $\sum({}_{s}w_i.\cos(\theta_i))$ (see Figure 7). The maximum shear crack width is estimated by Eq.7, where k_s is a calibration factor calculated as $k_s = \sum({}_{s}w_i.\cos(\theta_i)) / {}_{s}^{W}max$

$$ {}_{s}w_{max} = \frac{h_0.\delta_s}{k_s.h.\cos(\theta_i)} \tag{7} $$

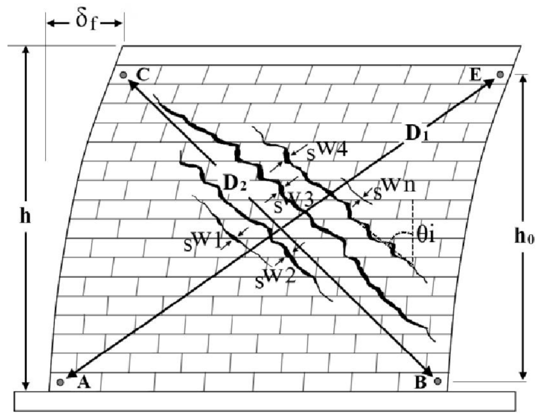

Figure 7. Shear crack model

4.4 Residual seismic capacity-maximum residual crack width relationship

Figure 8 shows the relation between the reduction factor and the maximum residual crack width of the tested walls. Additionally the maximum residual crack width which defines each damage level is presented. From this figure the following table is obtained:

Table 3. Damage level and η for Wall-A and Wall-B

Damage level	Crack width (mm)	η
I	W<0.4	0.9
II	0.4<W<3.0	0.5
III	3.0<W<6.0	0.2
IV	>6.0	0

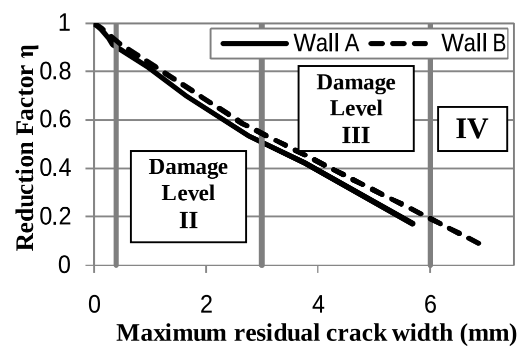

Figure 8. η-residual crack width

4.5 Residual seismic capacity and damage level state from a given maximum response

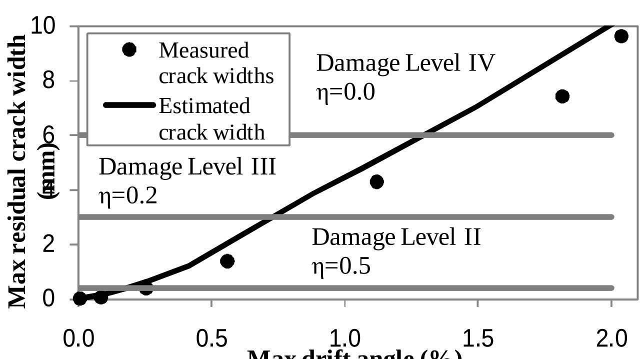

Figure 9. Calculated residual crack width

As a result of the procedure proposed in Figure 3, Figure 9 is presented. This graph shows the calculated maximum residual crack width for Wall-A. From this figure, an acceptable agreement between the measured and the calculated residual crack width can be observed. Additionally, the damage level and reduction factor presented in table 3 are shown in this figure. By means of these results, it is possible to judge the damage level and the residual seismic capacity of a block concrete wall from a given maximum response.

Considering that the fact that flexural crack was the widest in Wall-A, the estimation of the maximum crack widths was applied for the flexural deformation only. As a result of the calculation, a calibration factor k_f = 2.51 was used. It is worth mentioning that in a normal calculation, the shear and rotational cracks should be also calculated in order to select the maximum results of them (max (${}_{\mathrm{f}}w_{\max}$, ${}_{\mathrm{s}}w_{\max}$, ${}_{\mathrm{r}}w_{\max}$)).

It is important to mention that the applicability of the results is restricted to walls with similar geometrical properties, reinforcement and failure mode of the specimens used in this study. The importance of new experiments with variation in the characteristics of the specimens will be necessary to obtain widely applicable results.

5. CONCLUSIONS

Concretely, the relationships between the damage level and the residual seismic capacity for structural elements in block concrete houses are shown by using test data. Using this relationships and maximum response displacement of block concrete structure obtained by dynamic analysis, the procedure to evaluate the damage level of structural elements could be shown.

As for the investigation to estimate above relationships, the residual seismic capacity of masonry wall was calculated by using the residual crack width of structural elements. Secondly, the damage levels of this element were defined considering the damage state (serviceability, reparability, safety).

As for the investigation to propose above procedure, the whole calculation flow was shown in Figure 4. In order to complete this procedure, the method to estimate the residual displacement and the crack model to estimate crack width for the block concrete wall were proposed.

6. RECOMMENDATION

It is necessary to perform new structural tests to make the future guideline for damage evaluation of structural elements widely applicable.

It is strongly recommended that we should investigate the relation between the damage level of structural elements and buildings and define the residual seismic performance of building.

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