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# POST-EARTHQUAKE BUILDING SAFETY EVALUATION WITHIN THE PERFORMANCE-BASED DESIGN FRAMEWORK

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## *Abstract*

In 2017, Mexico City was hit by two severe earthquakes, the first occurred on September 7th (M 8.2), the second on September 19th (M. 7.1). While the first did not damage significantly any structure, hundreds of buildings were severely damaged during the second. Remarkably, buildings that did not undergo significant damage during the first earthquake, collapsed or underwent severe damage during the second one. This fact suggests that comprehensive building inspections after an earthquake could reduce the number of casualties produced by a second one. Throughout the emergency, the massive requirements for building inspections rapidly exceeded the Mexican government's capacity. The lack of a common protocol for post-earthquake inspection, and the deficiencies of government agencies to manage the huge amount of reports were evident. Thus, as a contribution to improve the emergency management for megacities based on the Mexican experience, in this paper, a post-earthquake performance-based building safety evaluation is presented. It includes not only traditional damage evaluation criteria, but also extended criteria to semi-empirically include the building's vulnerability. The use of subjective terminology is avoided. As an additional tool to facilitate the management of huge amount of information, interfaces to implement the protocol into a technological application (*app*) for mobile devices are included in an internet website.

The study is divided in three sections. First, the emergency framework is outlined, and the structural system is characterized. Typical damage patterns are presented. Second, vulnerability sources and structural damage are characterized within a Performance-based Framework through: a) *Post-Earthquake Damage index*, $D_i$, b) *Vulnerability index*, $V_i$, and c) *Dynamic amplification ratio*, $T/T_s$. Third, the markers for damage/vulnerability, namely green flag, yellow flag, and red flag are presented. Finally, the methodology is exemplified for a typical building, and the damage assessment compared with that established from non-linear analysis.

*Keywords: Post-earthquake evaluation, building damage assessment, building vulnerability, app for building inspection*

## 1. Introduction

In 2017, Mexico City was hit by two severe earthquakes, the first occurred on September 7th (M 8.2, epicenter at 745 km, depth 45.9 km), the second occurred on September 19th (M 7.1, epicenter at 122 km, depth 57 km). While the first did not damage significantly any building, the second one resulted in heavy damage in hundreds of buildings. Remarkably, buildings that did not undergo significant damage during the first earthquake, collapsed or underwent severe damage during the second one. This fact suggests that comprehensive building inspections after an earthquake could reduce the number of casualties produce by a second one.

Throughout the emergency, the massive requirements for building inspections rapidly exceeded the Mexican government capacity. Thus, personnel, staff and alumni from universities as well as other volunteers participated in the post-seismic damage assessment. After two months, more than 10,000 post earthquake inspections were carried out, and more than 7,000 buildings with different levels of damage were identified [1]. There were, however, hundreds of contradictory technical reports due to the lack of a common post-earthquake inspection protocol. Therefore, local authorities were forced to carry out additional inspections for final verification.

In parallel, government agencies had to deal with the huge amount of paper templates from building inspections. They were transcribed into electronic spreadsheets that were not always available to people affected by the earthquake or directly involved in public policy.

As a contribution to overcome these deficiencies, this paper presents a fast performance-based post-earthquake building safety evaluation. Subjective descriptions are avoided, and traditional damage evaluation criteria is extended to include relevant performance-based information. To facilitate the management of a huge amount of information, the development of a technological application (*app*) for mobile devices (smartphone or tablet) is proposed via interfaces to be included in an external website. The *app* would be a contributing factor for a more reliable post-earthquake inspection, and simultaneously, a useful tool for resource optimization during the emergency.

The scope of this paper is limited to medium-height reinforced concrete (RC) standard buildings, and low-rise masonry building structures. Non-structural damage is not explicitly covered.

## 2. Post-earthquake assessment framework

### 2.1 Government organization

In megacities, Emergency Committees are generally implemented after massive earthquakes to lead the government's response via public policies. The protocol proposed in this paper is summarized in Fig. 1. Fundamental steps to make it possible are: a) training of the technical staff, b) implementation of the post-seismic inspection protocol (including technological *apps*) and, c) management of information in real-time.

### 2.2 Staff for building assessment

The local authority in charge of the emergency response plan should define the responsibilities and minimum technical requirements for inspectors. Every inspector, however, should establish his/her own limits based on his/her knowledge and experience. It should be considered that rapid building inspections are not only useful to set priorities for the emergency response, but usually are the first contact that authorities have with the affected population after the earthquake. Thus, it is strongly recommended that field inspectors are prepared in social and psychological procedures to deal with stressed people, that usually experience earthquake-triggered anxiety, depression and/or phobias [2]. Also, the inspector should understand that although the procedure is superficial in nature, it is the basis that allows for the assessment of the building condition and, thus, have a strong influence on the decisions taken by the authorities.



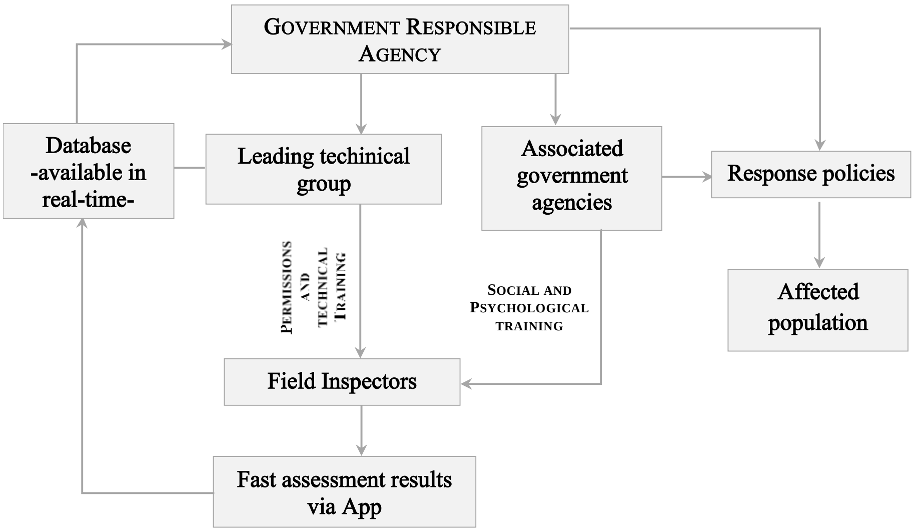



Fig. 1 – Proposed framework for emergency management

### 2.3 Characterization of the structural system and type of damage

During the emergency in Mexico City, erroneous conclusions were drawn due to misconceptions related to the structural system. For a proper identification of the structural system and its components, the following definitions shall be used:

i) Primary System: A set of elements that do not contribute to resist lateral seismic forces, but mainly sustain vertical loads.
ii) Secondary System: Devices that provide supplemental damping, or earthquake-resistant technology (not considered in the scope of this paper).
iii) Earthquake-resistant system: A set of interconnected structural elements designed to resist the seismic lateral forces.

In framed-buildings and masonry structures, the primary system and earthquake-resistant system generally coincide. In other common structural systems, such as dual systems in which frames are stiffened with walls or braces, frames may constitute the primary system, and the walls or braces the earthquake-resistant system.

Fig. 2 illustrates structural systems traditionally used for Mexican buildings. A more complete list of structural systems can be found in the Complementary Technical Requirements for Seismic Design of the Mexico City Building Code [3]. Fig. 3 illustrates the most common structural damage patterns caused by earthquakes. A detailed description may be found in related studies [4].

## 3. Damage and vulnerability indicators

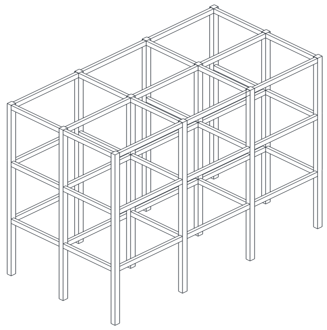
Traditionally, structural damage has been used as the predominant indicator for rapid post-seismic assessment. However, from the Mexican experience described in Section 1, additional vulnerability indicators shall be included in post-seismic assessment. Among others, it has been found that the structural configuration, material aging, soil-structure interaction and dynamic amplification of motion, can significantly affect the structural performance of a building [5]. As an alternative to the use of analytical vulnerability expressed through fragility functions, damage indicators are proposed:

1. Post-Earthquake Damage index, $D_i$.
2. Configuration vulnerability, $I_v$.
3. Dynamic amplification ratio, $R_T$.

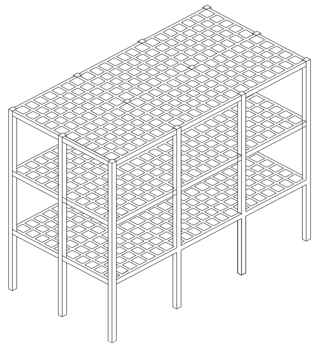


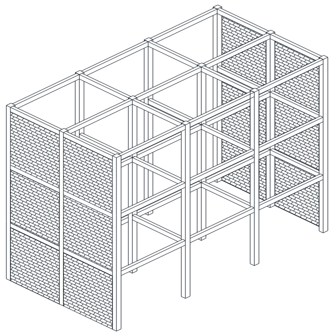
The inspector shall assign a different colour to each different type of risk marker, namely green, yellow or red flag. The global condition of the building is indicated with a placard, whose color indicates a performance range that contemplates two of the following four performance levels: Operational Performance ($O_P$), Immediate Occupancy ($I_O$), Life Safety ($L_S$), and Collapse Prevention ($C_P$). As shown in Table 5, the placard's colors are: green for $O_P$-$I_O$, yellow for $I_O$-$L_S$, and red for $L_S$-$C_P$.



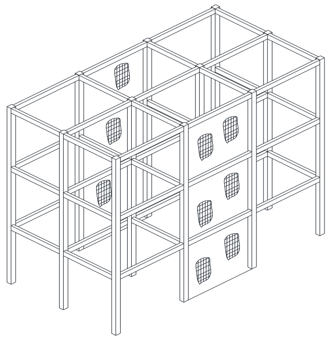
*(a) Framed building*



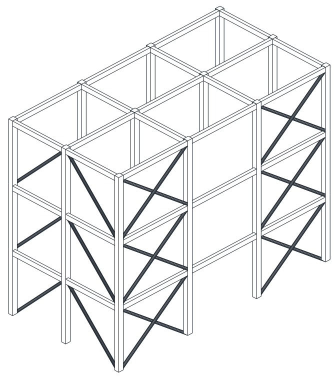
*(b) Two way waffle slabs + columns building*



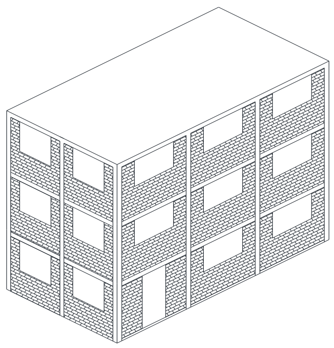
*(c) Framed building + masonry walls*



*(d) Framed building + RC walss*



*(e) Framed building + bracing*

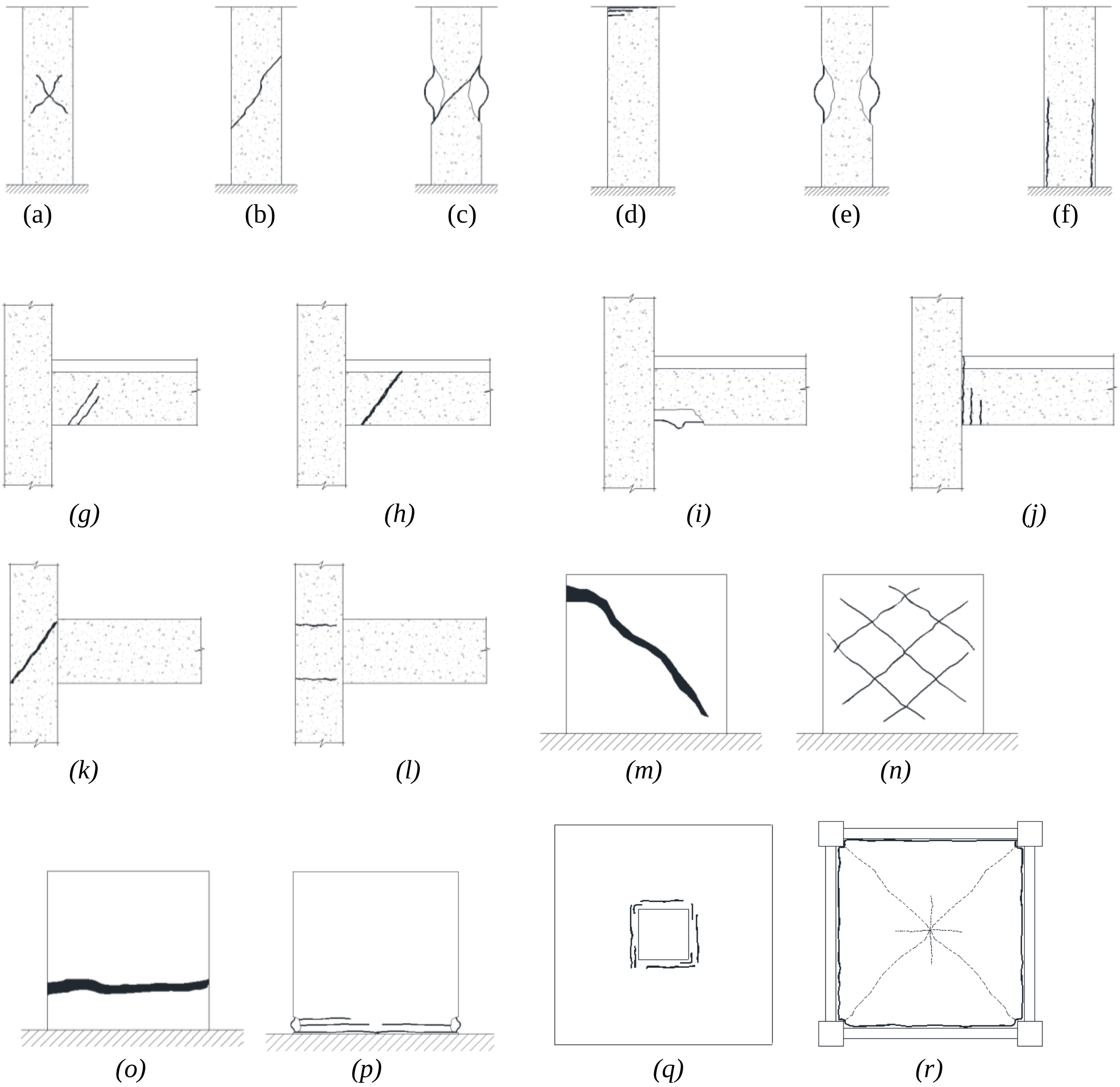


*(f) Confined masonry building*

Fig. 2 – Typical structural systems






*(a)*, *(b)*, and *(c)* shear damage on columns; *(d)* flexure damage, *(e)* flexocompression damage, *(f)* anchorage damage on columns; *(g)* and *(h)* shear damage on beams; *(i)* and *(j)* flexure damage on beams, *(k)* and *(l)* shear and anchorage damage on connections, respectively; *(m)* and *(n)* shear damage on walls; *(o)* and *(p)* flexure damage on walls; *(q)* and *(r)* shear and flexure damage on slabs, respectively.

Fig. 3 – Common damage on typical structural elements

### 3.1 Post-Earthquake Damage index, $D_i$.

This index associates structural damage to a corresponding performance level:

$$\text{Seismic demand} \leq \text{Earthquake-resistant capacity} \quad (1)$$

Assessing Eq. 1 in a simple and reasonable form for practical post-earthquake inspection requires experience derived from a large amount of study cases [6]. For performance-based structural damage assessment, Eq. 1



should be formulated in terms of deformation or lateral displacement. The proposed assessment methodology formulates the demand-capacity balance of deformation by adopting an indirect criterion based on comparing measured crack widths with preset limits established by experts as a function of the type of damage and the structural member involved. Cracking implicitly involves a seismic demand, that should be compared, for a given performance level, with an acceptable seismic capacity (preset crack width limits). While modern buildings designed according to current design practice should satisfy at least with the life safety performance level, older buildings may exhibit crack patterns that involve widths that exceed those established by experts for collapse prevention.

The manner in which a building behaves during an earthquake significantly influences its response. As shown in Fig. 4 (adapted from [7]), while shear and bending-type behaviors imply different cracking patterns with different allowable widths, allowable widths also depend on the structural material. Within this context, every structural element should be carefully inspected, and its contribution to the global stability and building safety evaluated. All performance-based design principles should also be checked during the inspection (strong column-weak beam ratio, allowable story drift, etc.). At this point, the professional experience, academic background, and knowledge of the inspector plays a crucial role during damage assessment, particularly in terms of avoiding an overly subjective interpretation of structural damage.

Damage assessment of non-structural elements may be consulted in other studies [8]. Damage in non-structural masonry walls that provide supplemental stiffeness to the building may be assessed with the criteria used in their structural counterparts.

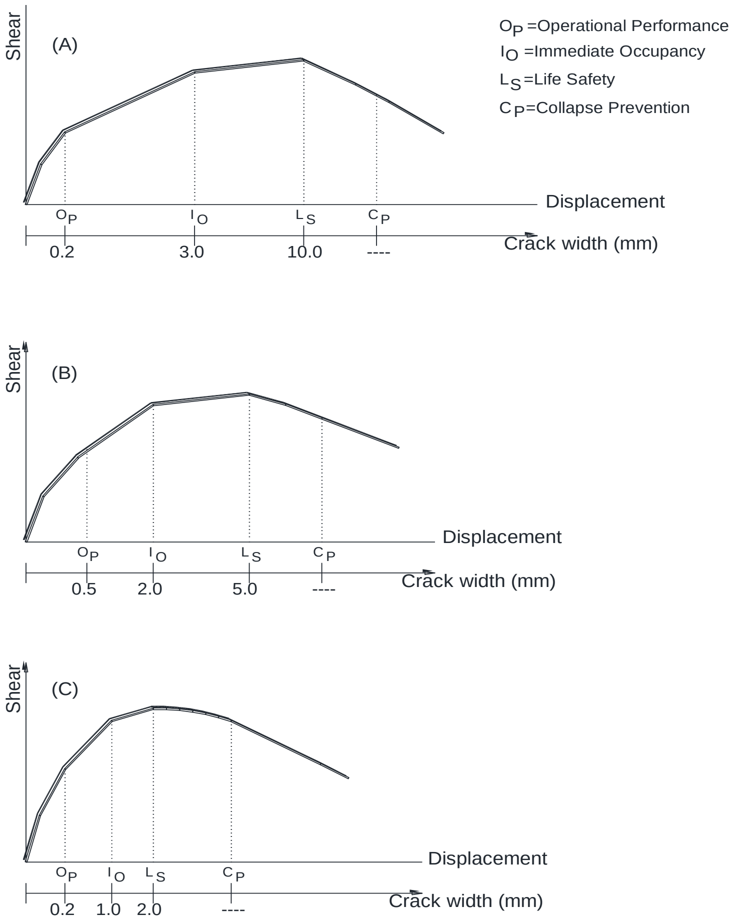



Fig. 4 – Common damage on typical structural elements –*(a)* for structural masonry, *(b)* for flexure-type RC and *(c)* for shear-type RC



### 3.2 Configuration Vulnerability, $I_v$.

This index includes the vulnerability conditions that may impose additional risk to the building. It quantifies threats from different sources, including a departure from the basic regularity conditions established by the Complementary Technical Requirements for Seismic Design of the Mexico City Building Code [3]. Table 4 shows penalty values for multiple structural irregularity conditions. The risk factors shown in Table 5 are associated to conditions established according to the Complementary Technical Requirements for Seismic Rehabilitation of Existing RC Buildings [9].

If all the conditions summarized in Tables 4 and 5 are satisfied, $I_v = 1$. For each unsatisfied condition, the penalty value indicated in the tables for that condition is added to $I_v$. The color marker is assigned according to (see Table 5): a) for $I_v = 1$, green flag, b) If $1 < I_v < 2$, yellow flag and, c) if $2 \geq I_v$, red flag.

The penalty values under consideration in Tables 4 and 5 are semi-empirically based on design criteria established in the Complementary Technical Requirements for Seismic Design for irregular structural systems (0.8 for irregular buildings and 0.7 for very irregular buildings).

Table 1 – Regularity conditions

| | **Condition** | **Penalty value** |
|---|---|---|
| 1 | The walls, frames and other vertical earthquake-resistant systems are significantly parallel to the orthogonal axes | 0.10 |
| 2 | The ratio of building height to the smallest base dimension is not greater than four | 0.10 |
| 3 | The ratio of the length to width of the base is not greater than four | 0.10 |
| 4 | The plant has no entrant corners or projections exceeding 20 percent of the dimension of the plant, measured in the parallel direction in which they are considered | 0.10 |
| 5 | The weight of each level is not greater than 120 percent of the corresponding to the immediately lower floor | 0.10 |
| 6 | In each direction, no floor has a plan dimension greater than 110 percent of the immediately inferior one. Additionally, no floor has a plan dimension greater than 125 percent of the smallest dimension of the lower floors in the analyzed direction | 0.10 |
| 7 | Each floor system may be assumed as a rigid diaphragm | 0.2 |
| 8 | The floor system has no openings that exceed 20 percent of the floor area, and the hollow areas do not differ in position from one floor to another. The last floor is exempted of this requirement | 0.2 |
| 9 | In each level, all columns are restricted in the two analysis directions by horizontal diaphragms or beams. Therefore, no column passes through a floor without being bounded to it | 0.2 |
| 10 | All the columns for each floor have the same height, although it may vary from one floor to another. The last floor is excluded of this requirement. | 0.2 |
| 11 | The lateral stiffness of any floor differs by more than 20 percent from the immediately inferior one. The last floor is excluded of this requirement. | 0.2 |
| 12 | In no floor the lateral displacement of any point of the plant may exceed 20 percent the average lateral displacement of its extreme edges | 0.2 |

### 3.3 Dynamic amplification ratio, $R_T$.

This ratio considers a possible dynamic amplification of the ground motion. The ratio of the building period, $T$, to the soil period at its base, $T_s$, is calculated and compared to the following limits:



$$0.70 \leq T/T_s \leq 1.40 \quad (2)$$

While the soil period is established according to the Complementary Technical Requirements for Seismic Design of the Mexico City Building Code [3], $T$ may be approximated as [10]:

$$T = aN \quad (3)$$
$$T = aH^b \quad (4)$$
$$T = aH^bD^d \quad (5)$$

where $N$ is the number of stories, $H$ the height of the building, and $D$ the density of walls (calculated as the sum of the transverse areas of the walls in the analysis direction divided by the plan area). Values for coefficients $a$, $b$ and $d$, summarized in Tables 3 and Table 4, depend on the structural system and soil at the construction site. Depending on the value of $T/T_s$ the following two scenarios are considered (see Table 5): a) If the existing building exhibits structural damage and $T/T_s$ falls within the limits of Eq. 2, it is assumed that dynamic amplification occurred and a *yellow flag* is assigned to $R_T$; b) If $T/T_s$ falls out of the range considered in Eq. 2, it is assumed that no dynamic amplification took place and other causes of damage should be investigated (in this case a *green flag* is assigned to $R_T$).

Table 2 – Additional vulnerability sources

| The penalty values for each condition is equal to 0.25 except condition 22 | | | |
|---|---|---|---|
| 13 | Soft or flexible first floor | 19 | Sloped ground, soil rupture or cracking |
| 14 | Slabs supported directly in columns | 20 | Ruptures in surrounding rocks/paving |
| 15 | Eccentric or off-axis connected elements | 21 | Tilt values exceeding allowable limits |
| 16 | Multi-familiar buildings | 22 | Add 0.05 for every 10% of building area with masonry damaged between $O_P$-$I_O$ |
| | | | Add 0.1 for every 10% of building area with masonry damaged between $I_O$-$L_S$ |
| 17 | Corrosion and aging in critical elements | | Add 0.15 for every 10% of building area with masonry damaged beyond $L_S$ |
| 18 | Imposed additional risk by neighbor structures (tilt, partial/total collapse, contact among buildings, etc.) | 23 | Differential settlements exceeding allowable limits |

Table 3 – Coefficients for period calculation of framed and masonry buildings

| | **Period** | **Firm soil** | **Soft soil** |
|---|---|---|---|
| Masonry buildings | $T=aN$ | $a=0.040$ | $a=0.073$ |
| Framed-buidlings | $T=aN$ | $a=0.100$ | $a=0.126$ |
| | $T=aH^b$ | $a=0.034$, $b=0.94$ | $a=0.036$, $b=1.01$ |

Table 4– Coefficients for period calculation of framed buildings stiffened with walls

| **Period** | **Firm soil** | **Soft soil** |
|---|---|---|
| $T=aN$ | $a=0.063$ | $a=0.102$ |
| $T=aH^b$ | $a=0.031$, $b=0.89$ | $a=0.017$, $b=1.13$ |
| $T=aH^bD^d$ | $a=0.037$, $b=0.90$, $d=0.06$ | $a=0.030$, $b=1.16$, $d=0.14$ |



## 4. Overview of the protocol for rapid post-earthquake inspection

The paper template of the proposed protocol, and the *Application Program Interfaces* (API) of the *app* can be found on the website of *KyōDynamics Consulting*, www.kyodynamics.com. Herein, the general characteristics and the procedure for rapid assessment are described. The inspection procedure collects similar information required in other protocols [6, 11], with emphasis in the data used for the assignation of color markers (Section 3). The inspector is required to fill in the following interfaces:

i. Building location (with a Google Maps® interface).
ii. Characteristics of the building and complementary information.
iii. Structural system characterization.
iv. Previous structural retrofitting or modifications to the original configuration.
v. Cracking measurement, story drifts and vulnerabilities.
vi. Post-Earthquake Damage index, $D_i$ and flag assignation.
vii. Configuration Vulnerability, $I_v$ and flag assignation.
viii. Dynamic amplification ratio, $R_T$ and flag assignation.
ix. Global performance assessment.

Table 5 summarizes how a placard is established for the building based on the color flags assigned to the different indicators. Note that a single red flag in any indicator ($D_i$, $I_v$, and $R_T$) is enough to assign a red placard to the building.

Table 5 – Assignation of color placard for buildings

| **Criteria for global assessment:**<br>**1. For three green flags a green placard should be assigned to the building**<br>**2. For one or more red flags a red placard should be assigned to the building**<br>**3. For any other combination assign yellow placard to the building** | | | | **Action to perform** | | |
|---|---|---|---|---|---|---|
| **Indicator** | **Flag color** | | | No further immediate action is requiered<br>*Low risk protocol* | Immediate detailed assessment<br>*Medium risk protocol* | Evacuation of building and urgent detailed assessment<br>*High risk protocol* |
| Damage assessment, $D_i$ | $I_O$ (G) | | | ✓ | | |
| | | $L_S$ (Y) | | | ✓ | |
| | | | $C_P$ (R) | | | ✓ |
| Configuration vulnerability, $I_v$ | $I_v = 1$ (G) | | | ✓ | | |
| | | $1 < I_v < 2$ (Y) | | | ✓ | |
| | | | $2 \geq I_v$ (R) | | | |
| Dynamic amplification ratio, $R_T$ | Yes (G) | | | ✓ | | |
| | | No (Y) | | | ✓ | |

## 5. Case of study

5.1 Application of the proposed methodology

The building under study is located in a northern neighborhood in Mexico City named *Lindavista*. It was impacted by the partially collapsed adjacent building and classified as a high-risk building. After the demolition of what remained of the neighboring collapsed structure, a rapid inspection was required to assess the structural safety of the building.

The seven-storey building has habitational use. The actual condition during inspection and a typical floor plan are shown in Fig. 5. The primary structural system is formed by forty-eight RC columns located in the intersection of longitudinal and transverse lines. There are RC shear walls in the transverse line *E* between lines *3-4*, and in the elevator shaft. However, RC walls are not a complete secondary system because they not fully resist the seismic forces. Non-structural masonry walls provide supplemental stiffness to the building. Due to the openings in its first floor, the building can be classified as a soft-story building. The floor system consists of flat grid slabs directly supported in the columns.


*(a)* Condition during the inspection *(b)* Plan of a typical floor

Fig. 5 – Building under study

The building condition was fully inspected with the proposed protocol. For the sake of simplicity, only the most significant results obtained from damage indicators (described in Section 3) are presented.

*Post-Earthquake Damage index, $D_i$.* The critical damage was found in the 6th story due to the impact of the adjacent building. Columns in the transverse line *A*, namely, *2A*, *3A* and *5A* were severely deformed in such a way that they reached, as shown in Fig. 6, the $C_P$ level. In the 1st story, crack widths of columns located in longitudinal lines *1* and *6* was, as shown in Fig. 6, between 1 and 3 mm. These columns reached the $L_S$ level. Other structural elements such as columns, floor slabs and RC walls remained in $O_P$ level. A damage survey of non-structural masonry walls was carried out. Most walls in $C_P$ level were in the 6th floor near the impact area. Masonry walls in $L_S$ level were observed throughout the building. After a holistic study of the damage underwent by the building under performance-based design concepts such as SCWB, a red flag is assigned to the *Post-Earthquake Damage index, $D_i$*.

*Configuration Vulnerability, $I_v$.* The building satisfies all conditions from Table 1 except 11 and 12. Therefore, 0.4 penalty points are accumulated (0.2 for condition 11 and 0.2 for condition 12). The building satisfies all conditions from Table 3 except 13, 14 and 22. The damage of non-structural masonry was quickly surveyed as: 50% of the total area of masonry walls reached the $L_S$-$C_P$ interval, and 20% of the total area of masonry walls remained in $I_O$ level. Then, the penalty points in this case are 5(0.1) + 2(0.05) = 0.6, and the total penalty points that must be added to $I_v$=1 are 0.4 + 0.6 = 1. Therefore, 2 ≥ $I_v$ implying that a red flag must be assigned for $I_v$.



*(a) Column 1G* *(b) Column 2A* *(c) Column 3A* *(d) Column 5A*

Fig. 6 – Damaged columns

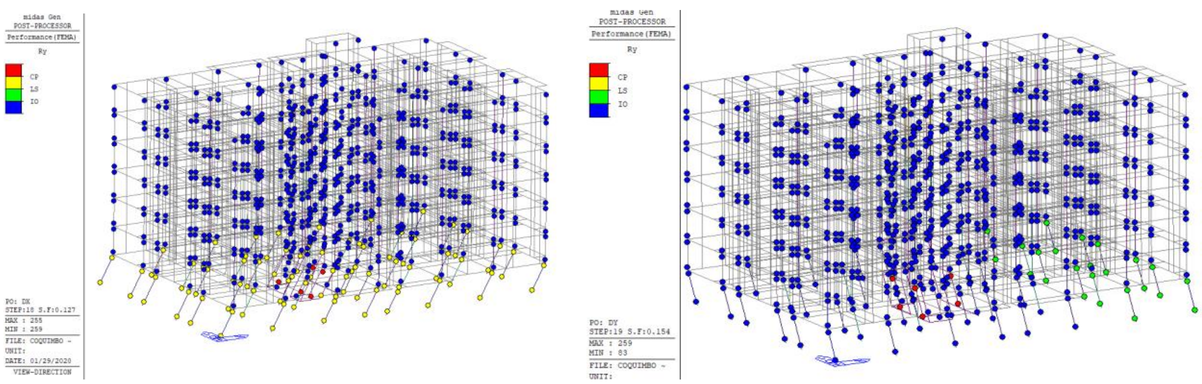
*Dynamic amplification ratio, $R_T$*. The period of the building estimated with the simplified procedure is $T$ = 0.88 sec with $H$=18.9 m. The soil period at the site is $T_s$ = 0.59 sec. The ratio $T/T_s$=1.49 falls out the limits of Eq. 2. Therefore, a green flag is assigned to the *Dynamic amplification ratio, $R_T$*.

*Building assessment*. There are two red flags and one green flag. According to Table 5 a red placard should be placed in the building and the protocol for high risk structure must be implemented.

4.2 Analytical verification

The building was modeled as a tridimensional system with the actual dimensions of the structural elements and characteristics of the structural materials. The analytical translational periods are $T_x$=1.21 and $T_y$=0.8 sec. The difference between the period calculated with the approximated equation is due to the torsion generated by the RC wall on transverse line *E*, between lines *3-4*. The ratio $T/T_s$ = 2.05 falls out the limits of Eq. 2, this result coincides with that obtained in the previous Section.

To verify the global performance of the building, a static nonlinear analysis was performed with Midas Gen®. The results in the two analysis directions are shown in Fig. 7. It may be observed that in both directions the building reaches the collapse prevention level, and thus, a red placard should be assigned to it. This result coincides with the placard assigned to the building in the previous Section.



*(a) Dir X* *(b) Dir Y*

Fig. 7 – Performace level of the building (pushover analysis results)



## 6. Conclusions

A rapid post-seismic inspection protocol based on Performance Design concepts was presented. The damage was characterized by cracking in structural elements and associated with the structural performance. Additionally, a semi-empirical approach to include two sources of vulnerability was presented. The first one is related to regularity conditions of the building. The second one is associated with the dynamic amplification of the building during an earthquake.

The application of the proposed protocol was exemplified through a case of study of an actual building. Nonlinear static analysis was performed for comparison purposes. Although the results obtained with the protocol are in good agreement with those from nonlinear static analysis, further research is needed to stablish robust indexes for vulnerability and dynamic amplification.

## 7. Acknowledgements

The post-earthquake inspection protocol reported in this study was presented to the Instituto para la Seguridad de las Construcciones del Distrito Federal, México, under the contract ISCDF/AD/PS-03/2018-20.

The *API* interfaces were developed by KyōDynamics Consulting under its *Green-based formulations*® project. Its support is greatly acknowledged.

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