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Review

Damage Index Seismic Assessment Methodologies of URM Buildings: A State-of-the-Art Review

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Abstract. This paper is written to review the previous studies of developing Damage Indices (DI) for Unreinforced Masonry (URM) Buildings. DI was designed to provide a critical indicator of damage states (DS), seismic vulnerability, and structural occupancy of buildings. DI approaches with simplified assessment methods to predict seismic vulnerability of URM structures are presented in this review, with the pros and cons of each assessment method are highlighted to propose an ideal methodology in using DI assessment. Thus, this paper is intended to provide a comprehensive information related to the state-of-the-art of DI methodology that can be used to seismically assess of URM buildings.

Keywords: URM, damage index, vulnerability assessment, failure mechanism.

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1. Introduction

Earthquakes are one of the most devastating natural disasters on earth that mainly causes severe destruction with high casualties. These destructions and loss of life caused by earthquakes have resulted in a need for proactive approaches for minimizing socio-economic losses and/or structural damage that may occur after an earthquake in seismically active regions. Thus, it is necessary to improve the safety of buildings by enabling reinforcement of existing structures in a realistic manner to withstand earthquakes above the predicted levels and building new structures that incur minimum damage in the event of an earthquake. If the possibility of damage to buildings could be predicted accurately at the design stage and operation lifetime, there would conceivably be less reason for drastic measures of protection.

Masonry structures comprise different masonry elements such as clay bricks, concrete block, clay tile structure, and stone. The main categories of masonry structures are unreinforced masonry (URM), confined masonry (CM) and reinforced masonry (RM) [1-3]. Masonry buildings are extensively constructed around the world, accounting for about 70% of the inventory of buildings [4, 5]. URM structures are found frequently in residential areas in the eastern and central parts of the United States.

URM building was originally constructed in United Kingdom and the architectural features were widely adopted in the commonwealth country, including New Zealand, Australia, and Northern Region of America. In addition, this construction system was employed in various countries with different architectural characteristics to the UK's URM buildings, with the prevalence of this buildings about 70% of the building inventory around the world [4, 5].

It is noticed that many masonry buildings have been damaged during recent earthquakes, since most of the structures were built without following the set of regulations and guidelines. Two main methods are used to assess the safety of masonry structures, which is influenced by the uncertainty resulting from data related to earthquakes and its mechanisms such as deformations, resistance, and actions. The first method is qualitative method which depends on collecting data that is related to the masonry structures and making surveys to gather the description and pattern of damage. On the other hand the second method is called the quantitative method, which relies on laboratory experimental tests and mathematical models. Damage or collapse of masonry structures usually occurs at the first-story level. Some researches such as Meli et al. [6] confirmed that the damage of masonry structures mainly effect the base walls of the first floor, and are considered a main priority to determine the degree of damage to masonry structures that have been exposed to earthquake incidents. Another approach for categorizing the damage of masonry buildings was done by Penelis et al. [7]. The approach depends mainly on the hybrid system, which emphasizes the economic side. The economic factor is the average of the cost of repair to the cost of reconstruction of the structure, in which it is deemed sufficient for the purposes of damage and risk assessment.

A significant number of URM buildings was observed to be constructed in seismically active regions [8-10]. The typical URM buildings were constructed prior to the development of seismic building code, thus these buildings are considered to be earthquake-risk [11-13]. For example, fifteen percent of residential buildings that are affected by the New Madrid Seismic Zone in the eight-state region of the United States are URM buildings [14]. Many of those buildings were constructed hundred years ago, which means that they are likely to encounter significant damage due to earthquake event.

Unreinforced masonry buildings showed poor performance as it was observed following the earthquakes around the world. Following the earthquake, one of the rapid assessment methodologies used to estimate the seismic vulnerability under a specific imposed ground motion by quantifying the damage was the Damage Index (DI) [15]. The degree of structural damage can be calculated by relating the dynamic response factors of an earthquake with appropriate structural capabilities. The seismic performance for URM buildings can be assessed by conducting seismic vulnerability assessment using Damage Index (DI) that can be used to express this building functionality and its occupancy [16-19]. These damage indices can be plotted into vulnerability curves that are considered to be a tool for the assessment of the structural deterioration through structural damage calculations. DI can also be used to assess construction damage, with the primary objectives of determining the safety of buildings and predicting the seismic vulnerabilities for different structures.

There are two types of DIs: (1): strength-based DI (SDI), and (2): response-based DI (RDI). The calculation of SDI does not require Finite Element (FE) analysis; it is measured against observed damage features through a large database. The RDI is, in turn, divided into three classes – deformation indices, cumulative indices and a combination of the two, the calculations of which require an FE approach [7, 20, 21].

In the past few years, several studies have investigated the development of appropriate material and finite element models to evaluate the seismic properties and the structural behaviour of masonry buildings. A variety of simplified methods of assessment has been used to predict the seismic protection of masonry buildings by determining the best damage indices [22-26]. For instance, three separate simplified indices (in-plan area ratio, area-to-weight ratio, and base shear ratio) have been assessed to determine the structural stability of historic masonry against earthquakes [27, 28]. Several approaches have been employed which, have involved the modification of these three indices [29-31]. The three indices and finite element methods have been integrated in a combined analysis method for developing an efficient damage vulnerability assessment tool [29, 32-34].

Most approaches have focused specifically on the structure vulnerability indices [35-40]. For instance, the vulnerability index formulation used by the national group for earthquake protection (Gruppo Nazionale Difesa Terremoti) GNDT and European Macroseismic approaches has been widely used in the European Union (EU) for identification and characterization of the possible damages that may result from earthquakes for a specific building or a set of different buildings using a point of qualification for each major element in the structure [41].

Most research studies that tackles of the DI have assessed structural deterioration and have performed structural damage calculations for different types of structures, mainly reinforced concrete buildings [42-51]. DIs proposed in the last 35 years have been for framed structures only and have not considered damage concentration in masonry structures, because the damage is not concentrated at a specific and known location of structural components. All of this has resulted in insufficient address of DIs in URM buildings. The DIs for URM buildings have largely originated from the main DIs with altered parameters or with new parameters.

In order to fill the gaps in knowledge which existed in the assessment of DIs in URM structures, there have been a few recent studies that focus on developing specific approaches of damage index assessment in these structures. This paper reviews the state of development of DI and the formulae that are used for URM buildings and assesses the need for more research in this area.

2. Common Failure Mechanism of URM Buildings

Extreme earthquake damage is usually seen in some areas around the world where earthquakes often occur, resulting in catastrophic collapse of buildings. These damaged buildings often have unreinforced masonry (URM) walls, known to be non-structural walls. URM walls can engage with boundary frames, elements in the structural design process. However, the construction engineers have paid less attention to their effects on structural efficiency. Damage assessments that have been conducted during earlier earthquake events have shown that the interaction of the infill-frame affects their performance as against bare RC frames, and often contribute to negative structural performance due to unintended failure mechanisms [52-54]. Therefore, the assessment of the seismic capacity of URM walls installed in boundary frames is urgently required to minimise the damage caused by earthquakes in those buildings [55-56].

Furthermore, during earthquakes, URM buildings cannot resist shear, tensile, and compressive stresses, due to the exceedance of those stresses with respect to the strength of URM buildings. However, the main problem is considered the ductility of URM buildings and not the strength of the building itself. In addition, the lack of sufficient connectivity between structural members is considered one of the main problems that face URM structures during earthquakes. Before developing DI for URM buildings, the failure mechanisms in those structures must be analysed [57].

The damages that occur in URM structures can be categorized into three types: absence of damage due to the structure that maintains its strength, moderate damage due to excitations in the final seconds, and total damage and collapse of the building [58]. Damages in URM buildings can also be classified in terms of their characteristics as described below.

- Out of plane damage for URM walls are further categorized into gable-end walls collapse, flexural cracks and walls overturning, mid height flexural cracks.
- In-plane damage for URM walls is represented by shear cracks (toe crushing, bed-joint sliding, diagonal tension, rocking).
- Damage at wall supports and corners are also considered in typical failure mechanisms [21, 59].

Figure 1 shows some typical URM failure mechanisms – out-plane failure, in-plane failure, flexural and shear deformations. In general, the damage mechanism tends to detach the masonry portions, where the damage could include various geometric shapes, which depends on the action and the type of masonry structures such as adobe buildings, brick masonry buildings, and stone masonry buildings.

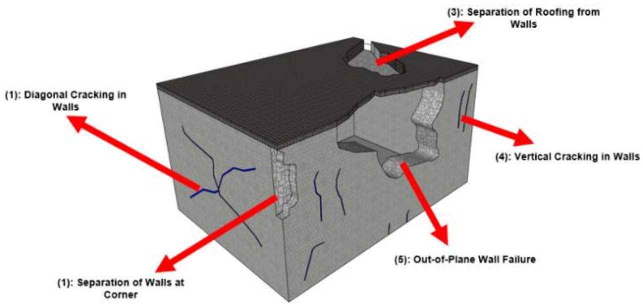

Fig. 1. Types of URM failure mechanism.

Adobe buildings are considered vulnerable to earthquakes because of the presence of heavyweight walls, which causes a larger resultant force on the masonry building as a result of the lateral movement of the ground. Moreover, adobe buildings lack in ductility and are thus considered very weak, resulting in abrupt tragic failures during earthquakes [60].

Failure of the masonry buildings is caused by detach of the main walls at the corners, detach of roofing from the walls or consequent failure of walls and cracking. These types of failure are shown in Fig. 2. However, separation of the floors and the roof can result from local stress concentration due to other factors. Some known failure mechanisms for adobe masonry buildings are: (1) Separation of walls at corners, (2) Diagonal cracking in walls, (3) Separation of roofing from walls, (4) Vertical cracking in walls, (5) Out-of-plane wall failure.

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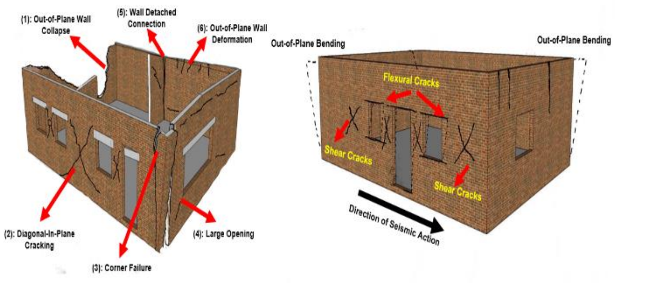

Fig. 2. Common failure mechanism for adobe masonry structures.

Some of the typical failure characteristics for brick masonry buildings are:

- Failure of corner junction causing an out-of-plane collapse is considered a major type of failure.
- Shear cracks in walls that are initiated at the main corners of wall openings.
- Out-of-plane failure for long spans at the wall topples due to reduced connections between the masonry walls at the roof and wall boundaries.
- Collapsing of walls causes a breakdown of floors and roofing, at critical cases a total building destruction can occur.

These failures highlight the significance of the following characteristics for brick masonry structures:

- Adequate bonding between the mortar and bricks – this is the primary factor for resisting in-plane shear collapse.
- Adequate bonding between the Wythes of walls – this can inhibit out-of-plane toppling.
- Adequate bonding between walls at the main corners or junctions – this will help in avoiding collapse of the masonry structures at the main corners or junctions, which is considered a typical failure characteristic for brick masonry structures.
- Adequate bonding between walls and floors or roofing – this will have a major impact on the stability of the masonry structure during earthquakes, as the failure of the roofing and floors results in a higher percentage of fatalities.

During earthquakes, different failure modes can occur for stone masonry structures that are:

- De-lamination: Usually stone masonry structures have two main external walls with loose rubble that are infill between for improved thermal efficiency, however these masonry walls are not properly attached to each other 'through' stones, they collapse and crack during any lateral motion caused by seismic actions.
- For long-span walls, the overturning occurs in out-of-plane.
- Mainly the bonding between exterior walls are of sufficient strength, the resistance of in-plane shear resistance for the masonry wall is deployed for the development of shear cracks.
- In many past earthquakes junction instability was observed leading to out-of-plane failure.

3. Common Damage Indices (DIs) for URM Buildings

The main problem of the URM is the absence of connectivity between structural elements, which has resulted in the need to develop DI's specifically for URM structures [28].

Many simplified methods have been developed to assess the performance of masonry structures during seismic events. For instance, DI based on three different simplified indices (area-to-weight ratio, in-plan area ratio, and base shear ratio), where the combined assessment damage index, damage index formulated based on flexible diaphragm, damage index as function of deformation and energy dissipation, and damage index based on demand capacity ratio, have been used to evaluate the safety of historic masonry structures during earthquakes. Furthermore, several studies have been conducted based on the analysis of DI modification for URM structures [61, 62]. Many researchers have also optimized the DI used for URM buildings by obtaining damage model, fatigue model, and softening model to apply a calibration index for URM buildings and have developed specific fragility curves for these URM buildings [63-66]. Most of the common DIs for URM buildings are area-to-weight ratio, in-plan area ratio, and base shear ratio. Figure 3 shows the types of damage index method used for estimating URM seismic assessment.

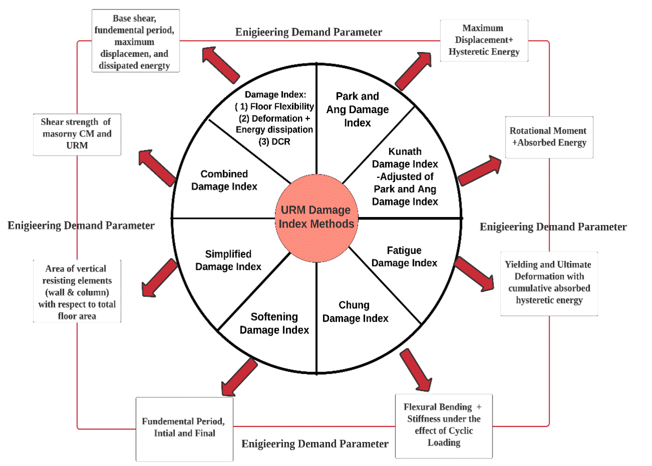

Fig. 3. URM damage index methods and their engineering demand parameters (EDPs).

3.1. Park and Ang Damage Index

The most common DI is the Park-Ang model; it is characterized by a combination of maximal deformation and hysteretic energy. Park et al. [63] developed a model that is based on both deformation and hysteretic energy resulting from earthquakes. This is the most widely used DI to date, primarily due to the general validity and clear description of different damage states [67]. This DI, which was subsequently modified by Park et al. [63] and Kunath et al. [68] is composed of two main categories, the ductility scaled category, and the dissipated energy category of the structural component under the effect of seismic movements, which is displayed in Eq. (1).

$$DI = \frac{U_m}{U_u} + \beta \frac{\int dE_h}{m r_y u_u} = \frac{u_m}{u_u} + \beta \frac{E_h}{F_y u_u} \quad (1)$$

where U_m represents the maximal displacement of a single-degree-of freedom (SDOF) structure during earthquake, U_u symbolizes the ultimate displacement under the effect of monotonic loading, E_h represents the hysteretic energy, r_y denotes the yield resistance of the structure, F_y represents the yielding force, is the parameter that is used to include the repeated loading effect and m represents the mass of the structure.

3.2. Kunath et al., Damage Index

Kunath et al. [68] modified the Park and Ang damage model using the moment-rotation and replacing it with the deformation definitions. Their equations are shown below:

$$DI = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{M_y \theta_u} E_k \quad (2)$$

where θ_m represents the maximal rotation that is obtained during loading, θ_u denotes the ultimate rotational capacity of a specific section, M_y symbolizes the yielding moment and E_k represents the energy which is absorbed by the section. Storey damage and global damage of the building are developed using weighted coefficients derived from the hysteretic energy of the members and storey levels using the following equations:

$$DI_{storey} = \sum (\lambda_i)_{component} \times (DI_i)_{component} \quad (3)$$

$$(\lambda_i)_{component} = \left(\frac{E_i}{\sum E_i} \right)_{component} \quad (4)$$

$$DI_{overall} = \sum (\lambda_i)_{storey} \times (DI_i)_{storey} \quad (5)$$

$$(\lambda_i)_{storey} = \left(\frac{E_i}{\sum E_i} \right)_{storey} \quad (6)$$

where λ_i represents the weighted coefficient based on hysteretic energy and E_i denotes total energy that is absorbed by the structural member or storey.

3.3. Fatigue Damage Based Model

Reinhorn and Valles [65] proposed a damage model. The model is based on the main structural response parameters and low-cycle fatigue law as shown in Eq. (7):

$$DI = \frac{\delta_a - \delta_y}{\delta_u - \delta_y} \times \frac{1}{\left(1 - \frac{E_k}{4\left(\delta_u - \delta_y\right) F_y} \right)} \quad (7)$$

where δ_a represents the maximum obtained deformation, δ_y denotes the yielding deformation capacity, δ_u symbolizes the ultimate deformation capacity, E_k represents the cumulative absorbed hysteretic energy and F_y denotes the yielding force.

3.4. Chung et al., Damage Index

Chung et al. [69] suggested a DI that measures the influence of the loading history and takes into consideration the variations between the positive and negative moments in the flexural response of the members. The consequence of the loading history is assessed by means of a specific parameter that includes the stiffness variation and the bending moments through the measurement cycle. Based on the curvature of masonry structures that usually react differently to positive and negative flexural behavior, the damage index is evaluated. The DI is calculated using Eq. (8) shown below:

$$DI_{CMS} = \sum_{i=1}^{n_{st}} \left(\alpha_i^+ \frac{n_i^+}{N_i^+} + \alpha_i^+ \frac{n_i^-}{N_i^-} \right) \quad (8)$$

where N_i represents the number of cycles that causes failure at curvature, n_i denotes the number loading cycles applied at curvature, α_i^+ with α_i^- are the damage modification factors, and +/- depicts the direction of load. The damage modification factors are specified based on the number of cyclic loadings of the earlier loading period.

3.5. Softening Damage Model

DiPasquale and Cakmak [66] developed a DI that relies on the ratio of the corresponding fundamental period, which is estimated from various ground motion records using period version of a linear model, and the fundamental period of the (undamaged) structures pre-earthquake. The usage of the fundamental period for the structure understudy as a main measure of stiffness degradation caused during earthquakes is considered the main parameter. However, the instantaneous fundamental period mainly relies on the damping and inertia forces. More details on the calculation procedure of the following damage index are described by Mitropoulou et al. [70] in Eq. (9).

$$DI = 1 - \frac{(T_0)_{initial}}{(T_0)_{equivalent}} \tag{9}$$

where T_0 represents the estimated equivalent fundamental period.

3.6. Simplified wall density index

Although, the wall density index is not considered a DI for assessing the masonry structures, it is still important to add this simplified index. Since it is considered as one of the most important assessment factors to study the seismic safety of masonry structures. Wall density index (I_W) is a simplified factor used in determining the seismic stability of masonry buildings, and typically used to direct the construction of the masonry structures. Many researchers have tested the simplified wall density index until it has arrived at the final formulation [29, 32, 71-73].

Lourenco et al. [29] provided a simplified in-plane index for earthquake resistant walls. The aim of this study is to compare geometrical data using three simplified indices and evaluate the main results to investigate the efficiency of this method. The first simplified index $\gamma_{1,i}$ is the simplest to determine the safety of masonry buildings, which performs the ratio of the area to the earthquake-resistant walls and the building's total plan area and can be calculated by using Eq. (10). Walls should only be deemed resistant to earthquakes if the thickness reaches 0.35 m or above and the height-to-thickness ratio is less than nine [74].

$$\gamma_{1,i} = \frac{A_{wi}}{s} \tag{10}$$

where A_{wi} represents the plan area of the resistant walls against earthquakes in direction i and s denotes the total plan area of the building.

For standard structures with rigid floor diaphragms, Eurocode (EC8) recommends values of up to 5-6 %, and for historical masonry structures, a minimum value of 10% seems to be suggested in cases of high seismicity.

The second simplified index $\gamma_{2,i}$ is the ratio between the earthquake-resistant wall plane area and the total construction weight, where the index is correlated with the building's horizontal cross-section per weight unit and can be calculated using Eq. (11). However, the main disadvantage of this index is that the formula for the fixed units must be evaluated. The minimum value that should be adopted in case of high seismicity is 2.5 m^2/Mn [28].

$$\gamma_{2,i} = \frac{A_{wi}}{G} \tag{11}$$

where A_{wi} represents the area of the resistant walls against earthquakes in direction "i" and G denotes the quasi-permanent vertical measure.

The third index $\gamma_{3,i}$ eventually implements the base-shear ratio that provides a safety function for the shear safety of the structure. The overall base shear for seismic loading ($V_{sd,base}$ = F_E) can be calculated from a horizontal static loading ($F_E = \beta G$) as shown in Eq. (12), where β is an analogous seismic static factor relative to the ground acceleration design. In a deeper analysis, the true value of β relies on the process of failure mechanism.

$$\gamma_{3,i} = \frac{f_{Rd,i}}{F_E} \rightarrow f_{Rd,i} = \sum A_{wi} f_{vk} \rightarrow f_{vk} = f_{vk0} + 0.4\sigma_d \tag{12}$$

where ($f_{vk\,0}$) denotes the cohesion factor and σ_d represent the design value of the normal stress, and $f_{vk\,0}$ can be a low or zero value in the absence of any additional information.

If zero cohesion is assumed Eq. (13) will be used for calculation:

$$\gamma_{3,i} = \frac{A_{wi}}{A_w} \times \frac{\tan\phi}{\beta} \tag{13}$$

If non-zero cohesion is assumed Eq. (14) will be used for calculation:

$$\gamma_{3,i} = \frac{\frac{A_{wi}}{A_w} \times \left[\tan\phi + \frac{f_{vk0}}{\gamma \times h}\right]}{\beta} \tag{14}$$

where h is the (average) height of the building, γ is the volumetric masonry weight, and ϕ is the friction angle of masonry walls.

Cai et al. [73] conducted a simplified wall density index I_w for CM and URM taking into consideration the main confinement components such as tie columns. Most previous studies have focused mainly on total floor areas without including confinement elements that are considered important as shear resistant components. The simplified wall density index can be calculated using Eq. (15). Figure 4 illustrates the main steps for calculating the simplified indices.

$$I_w = \frac{A_{wi} + n_1 A_{ci}}{A_{ft}} = \frac{A_{wi} + n_1 A_{ci}}{m A_f} \tag{15}$$

where A_{ci} represents the total horizontal cross-section area of reinforced concrete tie columns in "i" direction that can be assumed as zero for URMs, A_{ft} is the total floor area of masonry buildings, A_f is the plane area for each floor, m represents the number of floors, and n_1 denotes the maximum shear strength ratio of concrete (in tie column) with respect to masonry unit.

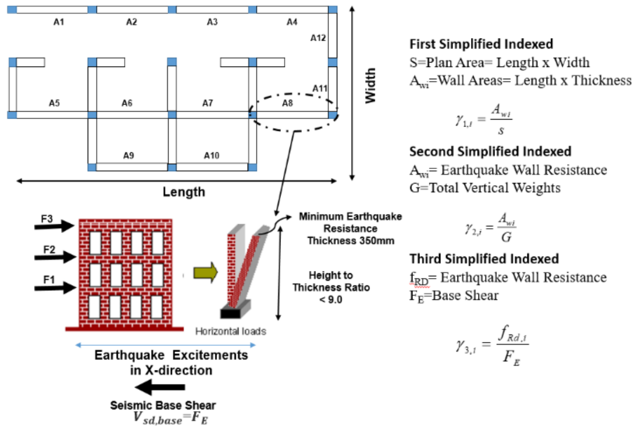

Fig. 4. Representation of the *Simplified index method.*

3.7. Combined Assessment Index

Cai et al. [73] developed the combined assessment index I_{sd} . A new combined index is developed for URM and CM buildings, taking into consideration the strength of the masonry walls and the enhancement impact of confinement components together. The approach is considered an equivalent index to this combined index to test the efficiency of seismic RC structures. With respect to CM and URM structures, Low-rise wall elements must tolerate shear deformation for masonry buildings. For this reason, the structural strength coefficient C_i of the URM and CM buildings is quantified as the shear strength per unit weight according to research results of Japan Building Disaster Prevention Association (JBDPA) and is shown in Eq. (16):

$$C_i = \frac{A_{wi} f_{vk,w} + A_{ci} f_{vk,c}}{G} \tag{16}$$

where $f_{vk,w}$ and $f_{vk,c}$ represents the attribute shear strength for all masonry walls and tie columns at the base storey of the building, and G is the total weight of the masonry buildings. In the case of CM, a reduction factor should be considered, while it should be reduced in URM because CM is influenced by confinement components such as tie beams, RC tie columns and rigid flooring. Nevertheless, no seismic engineering code was published to measure, quantifiably and clearly, the enhancement of confinement components in masonry buildings. However, Euro code 8 and JBDPA have recommended a specific strength reduction factor. In addition, this factor has been identified in Europe as a strength reduction factor for masonry buildings [75]. This factor can be calculated from Eq. (17):

$$R_i = \gamma_{ci} \gamma_{bi} \gamma_{si} \tag{17}$$

where the factor R_i represents a specified strength reduction factor for CM structures; the variables for this parameter are three enhancement coefficients, taking into account the effect of specific structural elements i.e., tie columns, tie beams and rigid floors on the seismic strength of masonry buildings. The reduction factors γ_{ci} and γ_{bi} that are used for URM buildings are equal to 1.0. γ_{ci} represents the increase ratio of the resistance capacities for masonry walls in relation with tie columns and it is calculated using Eq. (18).

$$\gamma_{ci} = 1 + \frac{T_{CM_i} - T_{URM\ i}}{T_{CM\ i}} \tag{18}$$

where T_{CMi} and T_{URMi} represents the axial tensile strength of masonry walls and both are determined by using Eq. (19) and Eq. (20):

$$T_{CMi} = f_{tkm} \left(\sum A_{wi} - \sum A_{ci} \right) + f_{tkc} \sum A_{ci} \tag{19}$$

$$T_{URMi} = f_{tkm} \sum A_{wi} \tag{20}$$

where f_{tkm} and f_{tkc} are the factors that affect the axial tensile strengths of the masonry structures and tie columns, A_{ci} and A_{wi} represent the total cross-section wall areas and tie columns.

The other two coefficients of enhancement γ_{bi} and γ_{si} are expressed as shown in Eq. (21) and Eq. (22):

$$\gamma_{bi} = 1 + \frac{n_1 \sum_{j=1}^{m} L_{qi,j}\ A_{qi,j}}{n_1 \sum_{j=1}^{m} L_{qi,j}\ A_{qi,j} + \sum_{j=1}^{m} L_{wi,j}\ A_{wyi,j}} \tag{21}$$

where $L_{qi,j}$ is the average horizontal length of tie beams, $A_{qi,j}$ is the total vertical cross-section area of tie beams, $L_{wi,j}$ is the average horizontal length of masonry walls, and $A_{wyi,j}$ is the total vertical cross-section area of masonry walls.

$$\gamma_{si} = 1 + \frac{\sum_{j=1}^{m} A_{b,j}\ h_{b,j}}{\sum_{j=1}^{m} V_j} \tag{22}$$

where $h_{b,j}$ is the thickness of the floor, $A_{b,j}$ is the plane area of the floor, V_j is the total volume of the floor obtained through the height (h_j) and plane area $(A_{f,j})$ of the floor, expressed as shown in Eq. (23):

$$V_j = n_1 A_{b,j}\ h_{b,j} + \left(h_j - h_{b,j} \right) A_{f,j} \tag{23}$$

The reduction factor can be expressed in a SDOF formula similar to that described by Tomaževiča and Klemenc [75] this structure's strength reduction factor R can be expressed as presented in Eq. (24):

$$R = \frac{F_e}{F_y} \tag{24}$$

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where F_e and F_y are the maximum elastic restoring strength and the yielding strength of SDOF systems, respectively; δ_u and δ_y are the yielding and ultimate displacement, which correspond to the above two strengths, respectively; u is the displacement ductility of the masonry buildings that is equal to the ratio of δ_u to δ_y, which are both usually calculated by conducting different experimental investigations.

The combined assessment index was performed in which JBDPA proposed a structural strength factor C_i. Both Eurocode 8 and Tomaževič and Klemenc [75] have provided strength reduction value R to be used to reduce the effect of the masonry structural elements on the seismic strength of masonry buildings. Overall, a combined assessment index I_{sd} is performed at various experimental conditions to evaluate the masonry structure performance and shown in Eq. (25):

$$I_{sd} = C_i R_i \tag{25}$$

3.8. Damage Index Formula for Masonry Building with Flexible Floor

Hadzima-Nyarko et al. [37] studied the DI for flexible floor-URM buildings and extended the research studies from RC buildings to masonry buildings, by using the results reported by Morić on masonry buildings [76,77]. The technique for conducting the DI was based on the structural capacity (DI_s) relationship with the structural response (DI_d). When $DI_s < DI_d$ the masonry structure resists earthquakes without collapsing. The results obtained are systematized to establish the correlation between the seismic resistance of masonry structure with rigid floors and with buildings of different floors structure by using Eq. (26).

$$DI = \frac{W_d}{2.4 BS_y \; U_y} + \frac{D_d}{3} + \frac{(T_i / T_0)_d}{1.5} \tag{26}$$

where $\frac{W_d}{2.4B \; S_y \; U_y}$ represents the dissipated energy where W_d represents the demand hysteresis energy dissipated during an earthquake, (BS_y), which represents the yielding base shear at ground floor (U_y), depict the yield displacement, $\frac{D_d}{3}$ the maximal displacements, by which D_d represents the demand displacement of the building, and $\frac{(T_i / T_0)_d}{1.5}$ is the variation of fundamental period T between 0.05 and 2 to study the variation the tolerance of target spectrum, where T_i is the base period in the i-th step for damaged building and T_0 is the base period for undamaged building. DI_{flex} is viewed as the mean value of partial seismic ratios acting as a variation of structural response parameters Morić [77]).

For URM structures, it is recommended to have the same as for confined masonry structures (CM) ($T = 0.05$, $BS_y = 0.1W$ and $K_2 = 0$), where BS_y represents the low elastic resistance buildings, and is calculated by considering W as a constant weight in kN and K_2 is factor which is related to post elastic behaviour it is always constant and equal to zero. Divided by the coefficient $DI / D_{flex} \leq 1$ according to the curves given as functions of the ratio $1/h$ and the type of ceiling as shown in Fig. 5.

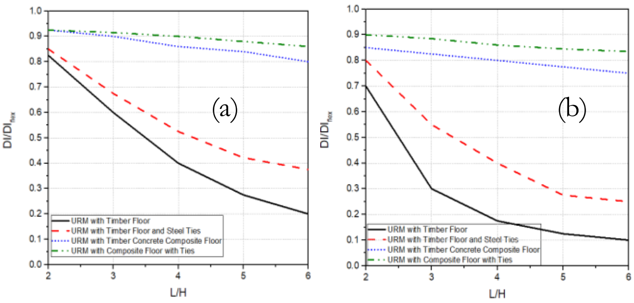

Fig. 5. Diagram relating DI / D_{flex} to $(1/h)$ for URM buildings up to three storeys, (a) $0.15 < f_t < 0.25$ MPa, (b) $f_t < 0.15$ MPa reproduced from Morić [71].

3.9. Damage Index as Function Deformation and Energy Dissipation

Remki et al. [78] proposed a damage model to evaluate the seismic performance of URM structures. In this model, the seismic damage is expressed as a function of the damage caused by excessive deformation and energy dissipation. This is formulated as a specific DI reflecting the damage model as shown in Eq. (27):

$$D = D_u + D_e \text{ In which } D_u = \frac{U_m}{U_f} \text{ and } D_e = \varepsilon \times \frac{\int dE}{q_u \times U_f} \tag{27}$$

where U_m: maximum displacement, U_f: Displacement at failure, $\int dE$: Hysteresis energy, q_u Shear force capacity, and ε: Constant ratio.

The damage index is calculated as a function of the total displacement and energy dissipation. In order to prevent potential failure, the damage should not be concentrated on a single floor; it should be evenly distributed along the floors. This culminated in a simpler way of distributing the harm appropriately across all floors of URM structures. Additionally, when the ratio of D_u *and* D_e is constant for all floors of URM structures, the damage distribution function will be developed by using Eq. (28):

$$R_D = \frac{D_i}{\sum_{j=1}^{N} D_j} = \frac{D_{ui}}{\sum_{j=1}^{N} D_{uj}} = \frac{\frac{U_{mi}}{U_{ui}}}{\sum_{j=1}^{N} \frac{U_{mj}}{U_{uj}}} \quad (28)$$

where N is the number of stories of URM building, mainly the response is provided by the first mode of vibration for low-rise masonry buildings, standard in plan and elevation. Furthermore, the damage distribution vector is calculated using Eq. (29):

$$R_d = \frac{\left(\frac{R_i}{U_{ui}}\right)}{\sum_{j=1}^{N}\left(\frac{R_j}{U_{uj}}\right)} \quad (29)$$

3.10. Damage index based on Demand-to-Capacity Ratio (DCR)

The damage index is a ratio of the seismic load to the structure's resistance. The seismic load is defined by the intensity of ground movement as a function of the root mean square acceleration E_a, according to the frequency in terms of predominant period T_g and the duration t_d.The resistance is represented by the stiffness of the basic period, and the capacity of the URM structure as a definition of ultimate displacement or ultimate strength. The DI for the SDOF system is established as represented in Eq. (30):

$$D = \frac{C\left(E_a, t_d, T/T_g\right)}{R\left(T, U_u\right)} \quad (30)$$

Equation (31) and Eq. (32) have been used for regression analysis according to Kwok and Ang [79]]:

$$C = \beta_1 \times h_{T_g} \times \left(E_a\right)^{\alpha 1} \times \left(t_d\right)^{\alpha 2} T \quad (31)$$

$$R = \beta_2 \times \left(T\right)^{\alpha 3} \times \left(U_u\right)^{\alpha 4} \quad (32)$$

where $\alpha_1, \alpha_2, \alpha_3$, and α_4 are exponents to be identified, β_1 and β_2 are constants, and h_{Tg} is a function of $T/T_g \le 0.7$ .If $T/T_g \le 0.7$ then $h_{T_g} = 1$, but, if $T/T_g > 0.7$ then $h_{T_g} = \frac{1}{\left(0.8\left(T/T_g\right)+0.44\right)}$. In case of SDOF systems, the method used for SDOF is generalised and used according to the previous relationships applied to the sum of the indices of damaged floors S_D, as given in Eq. (33) below:

$$S_D = \sum_{i=1}^{N} D_i = \gamma_N \times h_{T_g} \times \frac{\left(E_\alpha\right)^{\alpha 1} \times \left(t_d\right)^{\alpha 2}}{\left(T\right)^{\alpha 3} \times \left(U_{ue}\right)^{\alpha 4}} \quad (33)$$

where U_{ue} represents the ultimate equivalent displacement; expressed as being the sum of ultimate displacements of stories, γ_N is a constant. U_{ue} is expressed in Eq. (34):

$$U_{Ue} = \sum_{i=1}^{N} U_i \times R_{di} \quad (34)$$

According to Kwok and Ang [79] and studies done on several buildings for the variation of S_D and shown in Eq. (35):

$$\alpha_1 = \alpha_4 = \frac{\alpha_2 - \alpha_3}{2} \quad (35)$$

where $\alpha_2 = 0.35$ $\alpha_3 = -3.4 + 0.1N$ and $\gamma_N = 0.057 \times N^{-0.2}$. The range of URM structural systems is from 0.2 seconds for a firm soil to 0.8 seconds for a soft soil. Therefore, when the total sum of the indices of damage S_D and the vector of damage distribution R_d is known, the damage to the i_{th} floor can be calculated by using Eq. (36):

$$D_i = R_{Di} \times S_D = R_{Di} \times \gamma_N \times h_{T_g} \times \frac{\left(E_\alpha\right)^{\alpha 1} \times \left(t_d\right)^{\alpha 2}}{\left(T\right)^{\alpha 3} \times \left(U_{Ue}\right)^{\alpha 4}} \quad (36)$$

where the DI is shown using different dynamic parameters. These parameters have an influence mainly on the seismic damage of URM buildings. The variation of the DI depends on the root mean square acceleration E_α, duration of the strong motion t_d, structural period T, and the ultimate displacement U_u, which is represented in Fig. 4.

In the end, the results of the DI are compared to the damage limit DI_L, and if DI is greater than DI_L the building would not satisfy the seismic safety criteria and the URM building would need strengthening sin order for the building to achieve seismic safety. However, if DI is less than DI_l the URM building would satisfy the seismic safety criteria. Asteris et al. [26] have estimated a new DI for assessing the vulnerability of Unreinforced Masonry structures. A model that is based on the evolution of the damage for masonry structures is developed. The DI is formulated by dividing the percentage of the destroyed area of the masonry structure by the total area of this structure as shown in Eq. (37) below:

$$DI = \frac{A_{fail}}{A_{total}} \quad (37)$$

where A_{fail} represents the destroyed surface area for the masonry structure and A_{total} denotes the total area of the masonry structure. Various equations have been employed for expressing DI of masonry structures. An overview of the representative equations and methods for DI of masonry structures is presented in Table 1.

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Table 1. Existing DI equations that are used for vulnerability assessment of URM buildings.

Damage Index Method	Equation	Engineering Demand Parameters (EDPs)	Reference
Park and Ang Damage Index	$DI = \frac{U_m}{U_u} + \beta \frac{\int dE_h}{mr_y u_u} = \frac{u_m}{u_u} + \beta \frac{E_h}{F_y u_u}$	Maximum displacement and hysteretic energy.	Park et al. [63]
Kunath et al., Damage Index	$DI = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{M_y \theta_u} E_k$	Rational moment and absorbed energy.	Kunath et al. [68]
Storey Damage Index	$DI_{storey} = \sum (\lambda_i)_{component} \times (DI_i)_{component}$	Rational moment and absorbed energy.	Kunath et al. [68]
Global Damage Index	$DI = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{M_y \theta_u} E_k$	Rational moment and absorbed energy.	Kunath et al. [68]
Fatigue Damage Index	$DI = \frac{\delta_a - \delta_y}{\delta_u - \delta_y} \times \frac{1}{\left(1 - \frac{E_k}{4(\delta_u - \delta_y) F_y}\right)}$	Yielding and ultimate deformation with cumulative absorbed hysteretic energy.	Reinhorn and Valles [65]
Chung et al., Damage Index	$DI_{CMS} = \sum_{i=1}^{n_{st}} \left(\alpha_i^+ \frac{n_i^+}{N_i^+} + \alpha_i^+ \frac{n_i^-}{N_i^-} \right)$	Flexural bending and stiffness under the effect of cyclic loading	Chung et al. [69]
Softening Damage Index	$DI = 1 - \frac{(T_0)_{initial}}{(T_0)_{equivalent}}$	Fundamental, initial, and final period.	DiPasquale and Cakmak [66]
Simplified Wall Density Index	$I_w = \frac{A_{wi} + n_1 A_{ci}}{A_{ft}} = \frac{A_{wi} + n_1 A_{ci}}{mA_f}$	Area of vertical resisting elements with respect to total floor area.	Cai et al. [73]
Combined Assessment Index	$I_{sd} = C_i R_i$	Shear strength of CM and URM	Tomaževič and Klemenc [75]
Damage Index Formula for Masonry Buildings with Flexible Floor	$DI = \frac{W_d}{2.4B\ S_y\ U_y} + \frac{D_d}{3} + \frac{(T_i / T_0)_d}{1.5}$	Base shear, fundamental period, maximum displacement, and dissipated energy.	Hadzima-Nyarko et al., [37]
Damage index as a function deformation and energy dissipation	$D = D_u + D_e$	Base shear, fundamental period, maximum displacement, and dissipated energy.	Remki et al., [78]
Damage index based on demand capacity ratio	$D_i = R_{Di} \times S_D = R_{Di} \times \gamma_N \times h_{T_g} \times \frac{(E_\alpha)^{\alpha 1} \times (t_d)^{\alpha 2}}{(T)^{\alpha 3} \times (U_{Ue})^{\alpha 4}}$	Base shear, fundamental period, maximum displacement, and dissipated energy.	Kwok and Ang [79]
Damage index based on demand capacity ratio	$DI = \frac{A_{fail}}{A_{total}}$	Base shear, fundamental period, maximum displacement.	Asteris et al. [26]

4. Conclusions

This paper has critically reviewed extant literature on the damage indices used to assess seismic damage to URM buildings in the context of the historical evolution of DI. The most common damage indices that are used to assess URM buildings have been defined and described. Although a lot of work has been done until now in the field of DIs for URM buildings, few studies have focused on defining the critical parameters to be considered for the development of DI for URM buildings. This is an obvious area of future research and comparative studies may be carried out to assess and evaluate the main DI to be used for URM buildings. The DIs proposed in the last 35 years have been for framed structures and have not considered damage concentration, because damage is not concentrated at a specific and known location of structural components. Thus, most of these DIs are not applicable to URM buildings. For this reason, future research may need to create combined indices through combining different variable parameters and consider the connectivity among the structural elements of URM buildings. A few researchers like Su et al. [29] have developed combined damage indexes for masonry structures to quantify the enhancement effect of confinement elements on the seismic behaviour of CM structures, taking into consideration different damage indices for assessing URM and CM buildings. Such DIs for URM buildings could help in the classification and retrofitting of existing URM buildings.

To summarize, considerable efforts have been expended in developing DIs for assessing URM buildings, but gaps in understanding remain. Thus, future studies should focus on developing DIs that tackle failure mechanisms, which arise from the out-of-plane and in-plane damages, and damage at wall supports and corners. The type of the building – adobe buildings, brick masonry buildings, and stone masonry buildings – must also be considered while developing DIs for assessing URM buildings. Developing a DI model is indeed challenging but is critical for assessment of existing URM buildings and planning of new ones. Despite their limitations, damage indices are a powerful tool, and must be integrated into future construction and redesign operations, to pave the way towards more sustainable communities.

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