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Methodologies for the Evaluation of Seismic Risk in School Buildings in Near Real-Time

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Abstract

Seismic risk assessment studies are one of the most important references for measuring the losses caused by earthquakes and implementing mitigation actions. Fragility curves are widely preferred in these studies. This study proposes two methodologies for creating instant decision-making mechanisms in structural health monitoring applications. In the first method, appropriate fragility curves were utilized in the probabilistic assessment of the instantaneous damage state of the structure. Post-earthquake action plans were developed for different thresholds by establishing a relationship between structural damage and loss. Similar action plans were provided through the capacity curve in the second presented method. The two methods were tested for the existing school building considering different seismic hazard levels. While the methodologies presented in this study enable the creation of decision-making mechanisms for a single building, when applied to a group of buildings, they facilitate the rapid identification of critical locations in the immediate aftermath of an earthquake, enabling the estimation of loss of life and prediction of the extent of the disaster.

Keywords: Fragility curve, pushover, monitoring, damage, loss

1. Introduction

Seismic vulnerability and risk assessment studies are crucial for minimizing the damage caused by earthquakes and improving post-earthquake preparation. These studies are one of the most important tools for reducing human and economic losses. In addition, seismic risk and loss estimation studies enable public education and awareness raising, estimation of manpower requirements for disaster management, and budget planning. Another objective of seismic risk studies is to ensure that post-earthquake disasters remain manageable. The aim is to identify at-risk elements and critical areas and then to gain foresight into the potential losses.

Fragility curves are widely used tools for the probabilistic prediction of structural damage to a particular structure or group of structures. Generally, fragility curves obtained by considering analytical, empirical, hybrid, and expert judgment methods are mostly developed using log-normal distribution functions [1,2,3]. These curves are defined using two statistical parameters, the median and the standard deviation [4].

The fragility curve expresses the conditional probability of reaching or exceeding a predefined damage state (DS_i) for computed damage (d) under a certain ground motion intensity measure

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(IM). The mathematical expression of the curves is given in Equation 1.

$$P(d \geq DS_i | IM) = \Phi\left[\frac{1}{\beta_{DS_i}}\left(\ln\frac{IM}{\overline{IM}_{DS_i}}\right)\right] \tag{1}$$

Where, β_{DS_i} is the logarithmic standard deviation of the "d" conditioned on the IM, $\overline{IM}_{DS_i}$ symbolizes the median value of "d" under a certain IM value, and $\Phi(\bullet)$ represents the standard cumulative distribution function.

The first actions taken immediately after the earthquake are crucial to managing the crisis. Therefore, post-earthquake decision-making mechanisms based on scenario-based seismic hazard analyses are of utmost importance. Measuring structural damage or loss immediately after the earthquake and planning initial actions concerning the results obtained are one of the objectives of structural health monitoring (SHM) studies [5,6].

Due to the significant benefits it offers, SHM applications are increasingly popular and has become mandatory for some classes of buildings in Türkiye. Another purpose of using these systems is to monitor the instantaneous behavior of the structure and to provide data to enable immediate decision-making mechanisms. In most cases, the aim is to measure the instantaneous vibrations of the instrumented target structure. The existence of a region with a large number of instrumented structures will allow a more rational evaluation of many post-earthquake investigations. A case study is known in California, USA, where a large number of structures have been instrumented and monitored as part of the California Strong Motion Instrumentation Programme (CSMIP) [7].

The primary objective of this study is to develop a near real-time seismic risk assessment methodology for the target school building. The first method involves adapting fragility curves, which are widely used in seismic vulnerability and risk assessment, for SHM applications. This adaptation allows for the probabilistic analysis of the instantaneous damage state and facilitates rapid decision-making. The second method aims to evaluate the instantaneous damage state using the capacity curve. Using displacement sensors placed in the structure, the peak displacement value is calculated and then the damage state of the structure is estimated to predetermined thresholds on the capacity curve. Thresholds and explanations for the different damage states considered in the study are presented. For the critical damage state obtained for the two methods presented, alarm systems are activated, and the first actions to be taken immediately after the earthquake are determined. In case the methodology presented in this study is applied in a large number of buildings, it is believed that it will provide useful results in determining priority locations for post-earthquake intervention and for proceeding quickly and effectively after the earthquake.

2. Near Real-Time Seismic Risk Assessment Methodology

Within the framework of this study, two different methodologies are presented for the creation of post-earthquake decision mechanisms. A target school building located in Izmir, Türkiye was

selected to test the presented methods. The building is instrumented with the new generation accelerometers. However, it has not yet been subjected to a destructive earthquake. Therefore, these methodologies will be tested offline and decision-making mechanisms will be established.
In the study context, the flowchart of the near real-time seismic risk assessment methodology to be carried out using fragility curves is shown in Figure 1.

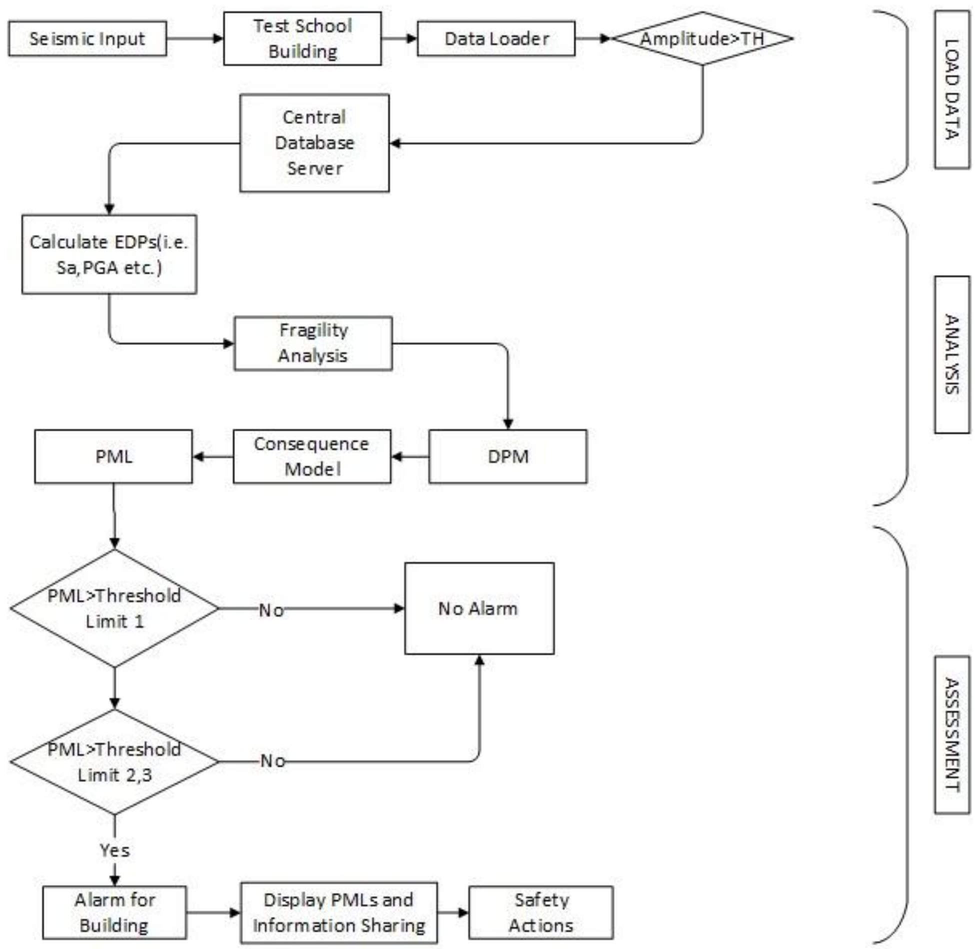

Figure 1. Basic steps of near real-time seismic risk assessment methodology

Figure 1 shows the basic steps of the near real-time seismic risk assessment for probable maximum loss (PML) values calculated using the fragility curves. The methodology consists of three main stages: Load data, Analysis, and Assessment.

Firstly, accelerometers placed at different locations of the target structure continuously monitor instantaneous ground motion vibrations. Then, during the instantaneous measurement phase, if the acceleration-time record exceeds the threshold level (TH) of 0.005 g amplitude, the system identifies a possible earthquake. Following this identification, the 10 seconds before the first exceedance of the threshold level are taken into account and transferred to the central database server, where the vibrations are permanently recorded for further processing.

The next stage is the analysis phase, where the intensity parameter considered in the fragility curve is calculated for the recorded acceleration-time record. Assuming that the fragility curves have been developed for Sa(g) and PGA, the values of these parameters are calculated first. The damage probability matrix (DPM) is calculated for the point of intersection of the calculated Sa(g) or PGA value on the fragility curves. The direct use of DPM may not give a precise idea of how to establish instant decision mechanisms. Therefore, PML calculations are proposed to establish a relationship between structural damage and economic loss in the presented methodology. In simple terms, the PML refers to the ratio of repairing damage cost to the structure after the earthquake to the reconstruction cost of the structure. In the final assessment phase, the computed PML value is evaluated according to the predefined threshold limits, and then the warning system and informational actions are performed.

Another method proposed, independently of fragility curves, is the creation of decision-making mechanisms for the maximum drift ratio (MDR) damage parameter. To this end, the capacity curves of the target structure and the defined threshold levels are shown in Figure 2.

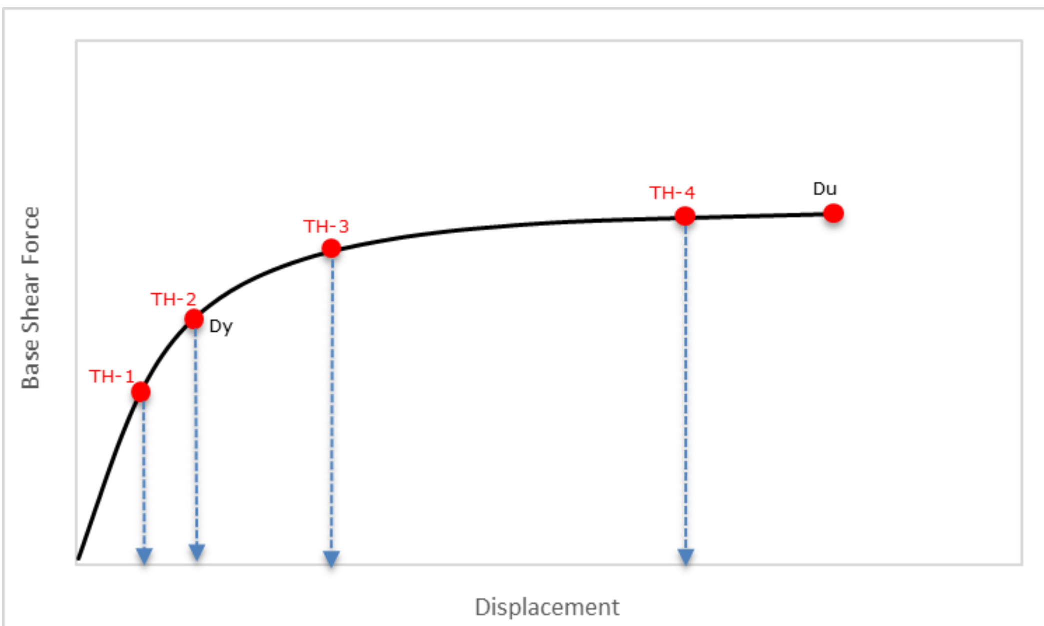

Figure 2. Determination of limits on the capacity curve

Using the critical points shown in Figure 2 as a reference, they are associated with the four threshold levels mentioned above. In this study, Threshold Level 1, Threshold Level 2, Threshold Level 3, and Threshold Level 4 values were determined as 0.7*Dy, Dy, Dy+0.2*(Du-Dy), and 0.75*Du, respectively. Therefore, in the evaluation to be carried out using the second method, the MDR is first calculated for both directions of the building through equipment located in different locations. The alarm level is then determined for the critical MDR value. It would be safer to consider both methods together and make decisions based on the critical method.

3. Case Study

The offline implementation of the presented methodologies is accomplished for an existing school building located in Izmir, Türkiye. This building is known to be instrumented and monitored. The 3-D finite element model of the building is shown in Figure 3.

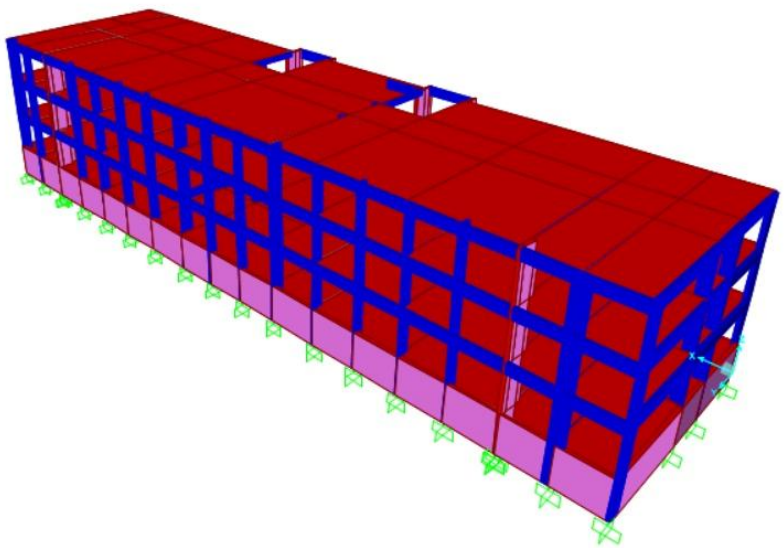

Figure 3. 3D numeric model of the existing school building

The considered building has recently been instrumented with accelerometers and has not yet been exposed to a destructive earthquake. For this reason, the seismicity of the location was determined using the target spectra computed by considering the DD-1 and DD2 seismic hazard levels expressed in TBSDC-2018 [8].

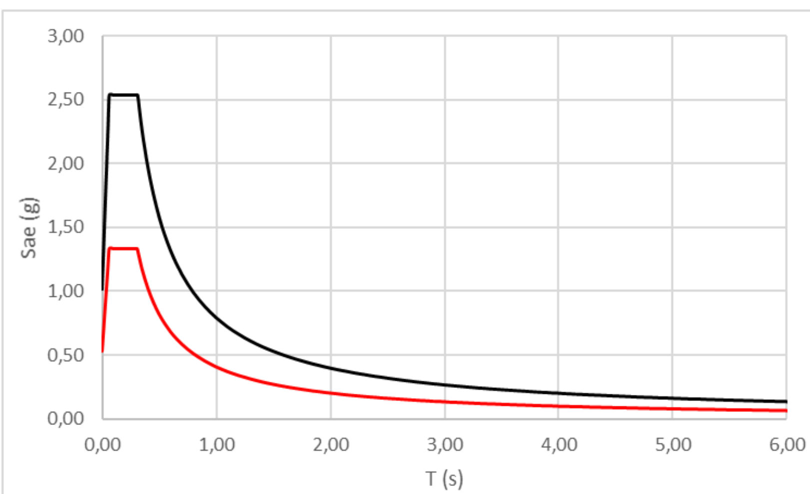

Figure 4. Target spectra for different seismic hazard levels

One of the critical steps of the presented method is the adequacy of the selected fragility curves in representing the structure vulnerability. Seismic vulnerability studies of school buildings in Türkiye are limited. In addition, the primary objective of this study is to test the methodologies presented. Therefore, the fragility curves presented by Martins and Silva 2021 for mid-rise school buildings, which were tested for suitability for this study, were utilized [9].

The vulnerability of the school building was evaluated using the appropriate fragility curves presented by Martins and Silva 2021 and given in Figure 5.

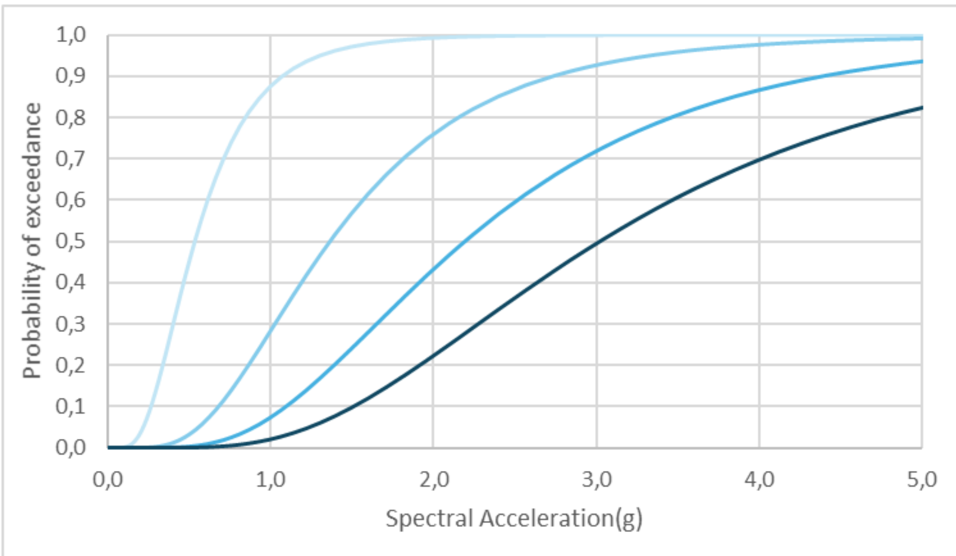

Figure 5. Fragility curves presented by Martin Silva 2021 for mid-rise school buildings

Considering the cracked section stiffness of the structure, Sa(T1,g) values were calculated as 0.93 g and 0.48 g for DD-1 and DD-2 seismic hazard levels, respectively. The DPM was then calculated using the calculated Sa(g) values and fragility curves. The DPM distribution obtained for DD-1 and DD-2 hazard levels is given in Figure 6.

It is difficult to determine the instantaneous precise damage state for the calculated DPM results of the structure. Therefore, this study focuses on the instantaneous economic loss value of the target structure. The probable maximum loss (PML) considered in this study represents the ratio of the cost of repairing the damage to the structure after the earthquake to the cost of reconstruction of the structure [10]. From an analysis of the studies in the literature, damage-to-loss functions (consequence models) have been identified which are suitable for proposed methods [11,12,13,14]. The consequence models taken into account in relating the structural damage distribution to the economic loss are shown in Table 1.

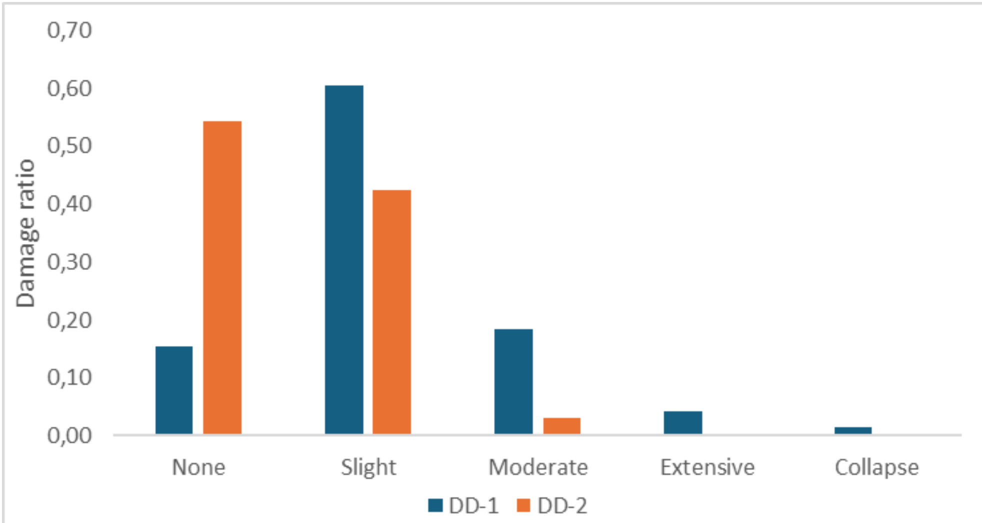

Figure 6. DPM values calculated for different seismic hazard levels

Table 1. Consequence models widely used in the literature

Damage State	Consequence Models (%)			
	Gurpinar et al. (1978)	Askan and Yucemen (2010)	DEE- KOERI (2003)	Bal et al. (2008)
None	0	0	5	0
Slight	5	5	20	16
Moderate	30	30	50	33
Extensive	70	85	80	100
Collapse	100	85	100	100

The following are examples of PML values calculated for the DD-1 seismic hazard level using the damage-to-loss functions given in Table 1.

$PML: 0{,}15 * (0) + 0{,}61 * (5) + 0{,}18 * (30) + 0{,}04 * (70) + 0{,}02 * (100) = 13{,}25\%\ (Gurpinar\ et\ al., 1978)$

$PML: 0{,}15 * (0) + 0{,}61 * (5) + 0{,}18 * (30) + 0{,}04 * (85) + 0{,}02 * (85) = 13{,}55\%\ (\text{Askan and Yucemen}, 2010)$

$PML: 0{,}15 * (5) + 0{,}61 * (20) + 0{,}18 * (50) + 0{,}04 * (80) + 0{,}02 * (100) = 27{,}15\%\ (DEE - KOERI, 2003)$

$PML: 0{,}15 * 0 + 0{,}61 * (16) + 0{,}18 * (33) + 0{,}04 * (100) + 0{,}02 * (100) = 21{,}7\%\ (Bal\ et\ al. 2008)$

Considering the calculations for the DD-1 seismic hazard level, the PML value (27,15%) obtained for the consequence model proposed by DEE-KOERI,2003 was found to be more critical. The alarm threshold levels of PML values for four different ranges are defined below to assess the calculated PML value.

- Threshold Level 1 (PML (%) = 0-10): This refers to the level at which educational activities can continue safely and uninterrupted within the building.

- Threshold Level 2 (PML (%) = 10-20): This level indicates the plastic/permanent deformations in the structural elements; therefore, uses such as gas and electricity should be stopped.
- Threshold Level 3 (PML (%) = 20-40): This level means that educational activities in the building should stop and the building needs to be assessed by seismic/structural experts. This is the level at which retrofitting is likely to be required, after which education can be resumed.
- Threshold Level 4 (PML (%) = 40-100): This is the level that indicates the necessity of rapid evacuation of the building without further evaluation. It usually refers to the level where the structure is likely to have partially collapsed.

The critical PML values calculated for the earthquake hazard levels DD-1 and DD-2 are 27,15% and 12,98% respectively. The system presented is expected to alarm at level 3 for DD-1 and level 2 for DD-2.

As a result of the step-by-step application of the presented methodology, it has been shown in a case study that instantaneous earthquake records obtained from instrumented target structures can predict the current damage state of the structure immediately after the earthquake. As mentioned before, in the second method, the capacity curve of the target structure is used for the evaluation. The capacity curves obtained for both directions of the selected building are given in Figure 7.

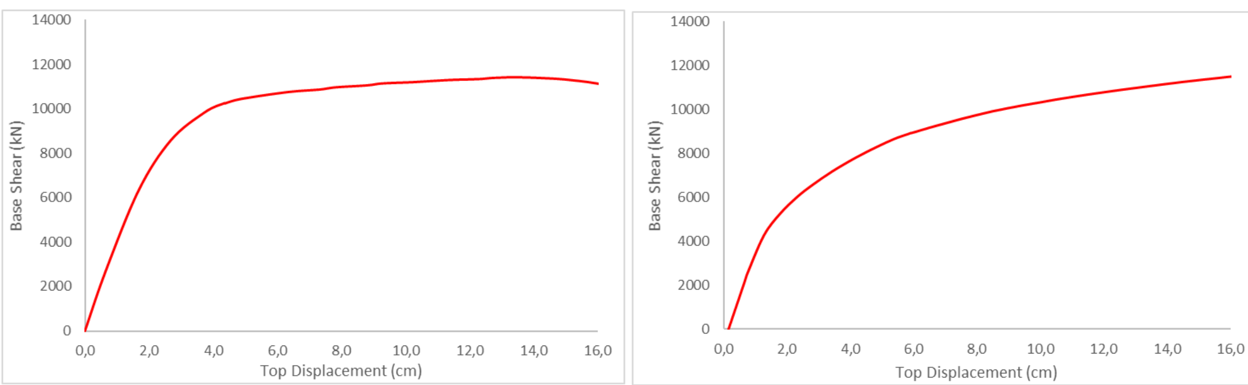

Figure 7. Capacity curves in both directions; X direction (left), Y direction (right)

The MDR limits vary depending on the structural and geometrical characteristics of the structure under consideration. The four limit values have been calculated for both directions of the target structure and are given in Table 2.

Table 2. Recommended MDR (%) limits for both directions of the structure

	TH-1	TH-2	TH-3	TH-4
X-Direction	0,290	0,415	0,808	1,786
Y-Direction	0,117	0,168	0,448	1,179

The considered structure has not yet been subjected to an earthquake. Therefore, it is currently not possible to calculate the MDR through accelerometers/displacement meters. However, the action to be taken in case the structure is exposed to an earthquake has been explained. First, the MDR value can be calculated using the acceleration-time records obtained for both directions of the structure from the accelerometer located at different points of the target structure, or it is also possible to calculate the MDR directly from displacement measurements. Then, taking into account the limits given in Table 2, it is possible to predict the current damage state of the structure immediately after the earthquake.

Conclusions

The objective of seismic vulnerability and risk studies is to measure the potential damage or loss to a specific building class in the event of an earthquake. Risk studies conducted before an earthquake aim to mitigate anticipated losses to a manageable level. Furthermore, the establishment of action mechanisms in the aftermath of the earthquake, with reference to seismic risk studies, presents a potential outcome.

This study aims to develop a decision-making mechanism that can rapidly generate initial actions immediately after an earthquake. To this end, two methodologies are presented for consideration. In the first method, fragility curves, which are widely preferred in seismic vulnerability and risk assessment studies, are adapted for use in SHM applications. This method enables the calculation of probabilistic damage distribution and structural loss in near real-time. Furthermore, distinct threshold levels were established based on PML, through the correlation of damage with loss. The second method involves the estimation of the instantaneous damage state of the structure using the displacement values obtained from the instruments in the target structure together with the capacity curve. The combination of the new-generation accelerometer network, which monitors seismic movements, and software tools that estimate seismic damage, will enable the execution of a near real-time seismic risk estimation for a pilot site in the event of an earthquake. To evaluate the proposed methodologies, an existing school building in Izmir, Türkiye was instrumented with new-generation accelerometers. As the structure has not yet been subjected to a destructive earthquake, the assessments were conducted offline. If the study is implemented on a large scale, the initial assessments of structural damage following an earthquake will be conducted automatically. This will facilitate the identification of the initial intervention points and provide rapid insights into the extent of the disaster.

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