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Seismic Loss Estimation of Precast RC Industrial Structures Using Appropriate Intensity Measure Parameters

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Abstract

Seismic vulnerability and risk assessments constitute a key component of disaster risk reduction strategies aimed at minimizing casualties and economic losses. The accuracy and reliability of these assessments depend on post-earthquake damage data, which provides valuable insights into the performance of structures during earthquakes. This study focuses on single-story precast RC industrial buildings that were damaged during the Mw 7.7 and Mw 7.6 Kahramanmaraş earthquakes on 6 February 2023. Common types of structural damage were identified through detailed on-site inspections of the affected buildings. Subsequently, analytically-based fragility curves were developed for a representative, typical single-story precast RC building model using different intensity measure parameters. In the final part of the study, the influence of various intensity measure parameters on seismic loss estimation was evaluated comparatively by calculating Probable Maximum Loss (PML) values through the integration of fragility curves and damage-to-loss functions.

Keywords: Fragility curve, incremental dynamic analysis, precast structure, seismic loss

1. Introduction

On February 6, 2023, two consecutive earthquakes struck south-eastern Turkey, causing widespread destruction and loss of life across the region. Based on data issued by AFAD, two strong earthquakes, Mw 7.7 and Mw 7.6, occurred nine hours apart at the epicenters of the Pazarcık and Elbistan districts of Kahramanmaraş on February 6, 2023. The focus depths of the earthquakes were 8.6 km and 7.0 km, respectively. The related report of MTA stated that the epicenter of the first earthquake was located approximately 35 km south of Kahramanmaraş, in an area between the 82 km long Pazarcık Segment and the Narlı Fault, on the main branch of the East Anatolian Fault. The epicenter of the second earthquake was located about 60 km north of Kahramanmaraş, on the 85 km long Çardak Fault, which is on the northern branch of the East Anatolian Fault [1-4]. The earthquakes were felt with extreme intensity over a vast area, particularly in Kahramanmaraş, Hatay, Adıyaman, Gaziantep, Malatya, Kilis, Diyarbakır, Adana, Osmaniye, Elazığ, and Şanlıurfa. The earthquakes caused the loss of thousands of lives, injured tens of thousands of people, the collapse of thousands of buildings. Immediately following the main shocks, thousands of aftershocks with magnitudes ranging between 3.0 and 6.0 were recorded (Figure 1).

The earthquakes caused extensive damage to various types of structures, with single-story precast reinforced concrete (RC) industrial buildings being particularly affected. In the post-earthquake damage assessment conducted by Yüksel and Çalım (2023), a total of 394 precast RC industrial

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buildings in the affected region were examined. The findings indicated that 57 buildings sustained heavy damage, 119 experienced moderate damage, 116 had minor damage, and 102 remained undamaged [5]. Industrial zones in five provinces within the earthquake-affected region were surveyed by Sagbas et al. (2024). During the field investigations, the performance of 131 industrial facilities was assessed, and 18 meetings were conducted with industry representatives. The study reported that the earthquake sequence had a considerable impact on industrial facilities, resulting in significant economic losses and work interruptions ranging from three months to two years. Based on the findings, the most severely affected facilities were those constructed before 2000, particularly structures featuring precast roof girders and columns with pinned connections at column tops [6].

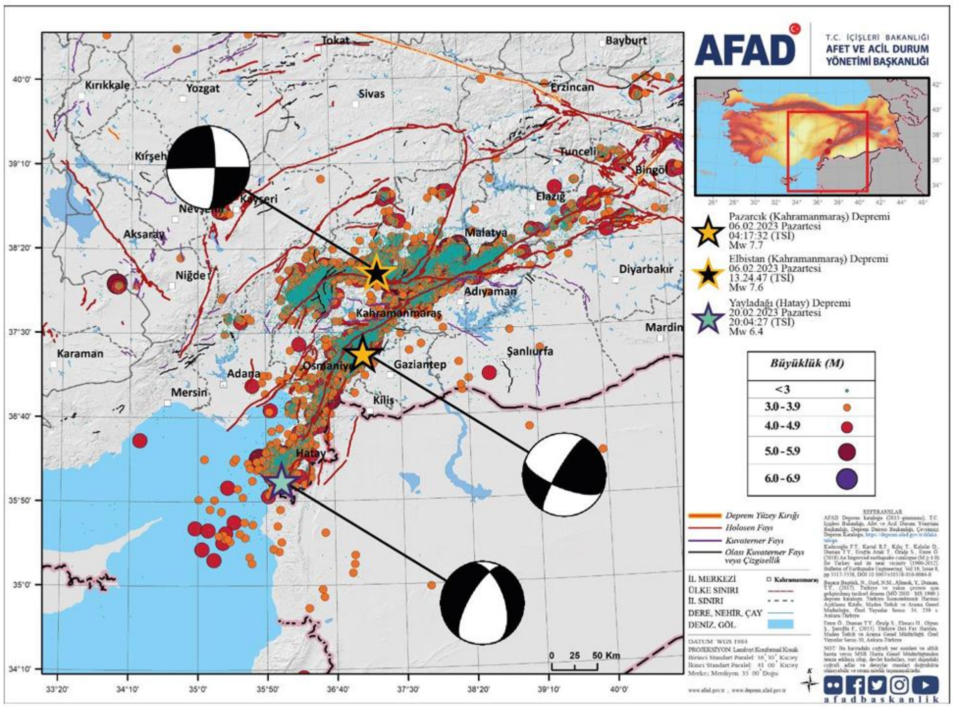

Figure 1. The seismic activity location map of the region between February 6, 2023, and May 6, 2023 [1].

Damaged precast structures following the Kahramanmaraş earthquakes were investigated in field studies conducted by Arslan et al. (2024). The study concluded that one of the primary causes of damage in precast RC industrial buildings was the inadequacy of connection elements. Moreover, the utilisation of grout mortar was proposed as a method to improve the load-bearing capacity of the connected components [7]. Similarly, a study conducted by Öztürk et al. (2024) revealed that the most prevalent types of damage in precast structures were inadequate connections between columns and beams, the formation of plastic hinges in columns, and the collapse of cladding wall panels [8].

Lastly, Kırtel et al. (2024) investigated the damages observed in industrial buildings with various structural systems and identified the underlying causes of these damages through field observations. Additionally, a three-dimensional nonlinear numerical analysis was performed on a three-story incomplete industrial building that was damaged due to the earthquake. Based on the results, the study emphasized the importance of improving the quality of construction materials, ensuring that reinforcement steel complies with ductility requirements, and implementing rigorous quality control measures during the construction phase [9].

2. Structural performance of Precast RC Buildings

A precast structure refers to a building system in which structural elements are mass-produced in factories using various procedures and then assembled on-site using specialized methods. These structures are classified into different categories based on the materials used, production processes, assembly techniques, and structural systems. Generally, single-story reinforced concrete (RC) precast RC industrial buildings consist of columns that are fixed in sockets at the base and are connected to precast roof girders at the top with pinned connections.

Single-story precast RC industrial buildings are commonly used in Organized Industrial Zones (OIZs) across Turkey. The main reasons for this preference include better control of production conditions, the ability to apply technological advances and engineering practices, and the reduced impact of construction variables compared to traditional on-site methods. Automation systems also contribute to labor saving and better control of material waste. Additionally, these structures are less affected by the weather due to the short construction time. Lastly, their cost-effectiveness is a key factor in their popularity for industrial buildings. The impact of the two destructive earthquakes that occurred on February 6, 2023, on existing single-story precast industrial-type structures in Adıyaman province has been investigated through field studies. The study identifies the common types of damage observed in the examined structures. These identified damage types are presented in Figure 2.

As clearly illustrated in Figure 2, based on inspections conducted on 15 structures in the region that sustained damage following the earthquake, plastic hinge formation was observed at the column-to-socket connection. Furthermore, in columns with larger cross-sectional dimensions, advanced plastic deformations were predominantly replaced by the development of microcracks. Moreover, plastic deformations were observed in the mid-span region of the column elements, accompanied by visible fractures at these locations. Similarly, significant damage was identified in the connection elements. In certain structures, even in the absence of plastic hinge formation at the column-to-socket connection, other forms of structural failure were documented, including the complete collapse of precast roof girders, gutter beams, and purlins, as well as fractures occurring in the mid-section of the columns. Although less common than the previously mentioned damage types, gusset damage was observed in some structures. Given the seismic map of the region, the level of damage exceeded expectations, with some buildings completely collapsing. While assessments are ongoing, one contributing factor appears to be non-compliance with current code requirements. Another significant factor is the inadequacy of connection elements. In several cases, although the column cross-section dimensions were adequate and no damage was observed in the column-to-socket area, deficiencies in the column-to-precast roof girder connections resulted in moderate structural damage.

Figure 2. Common types of damage observed in precast RC structures.

3. Seismic Vulnerability Assessment

In earthquake engineering, fragility curves are widely utilized as a risk assessment tool to estimate the probability of structural damage as a function of intensity measure (IM) parameters that characterize earthquake ground motion [10]. Fragility curves represent the conditional probability of a structure reaching or exceeding a specific damage state (DS), given a particular level of earthquake intensity measure (IM) [11,12]. Fragility curves are typically developed using empirical, analytical, or hybrid approaches. Empirical seismic vulnerability relationships were initially formulated in the early 1970s, primarily in the form of micro-seismic intensity functions.

In 1973, Whitman introduced the concept of Damage Probability Matrices (DPM) for multi-story buildings through an empirical methodology to estimate structural damage [13].

In analytical approaches, seismic vulnerability assessment is conducted by evaluating the structural response through numerical models. Commonly employed analytical approaches include nonlinear static analysis (pushover), nonlinear dynamic analysis, and displacement-based methods. Additionally, hybrid methodologies have been developed that integrate both empirical data and analytical modeling to enhance the reliability and accuracy of fragility curve estimations. Casotto et al. (2015) conducted nonlinear static analyses on 100 randomly selected precast industrial buildings that were damaged during moderate earthquakes in Northern Italy in 2012 to determine damage limit states. Using the cumulative percentage of buildings in each damage state for various earthquake intensity measures, fragility curves were developed. The results were also compared with empirical field data, showing a good level of agreement [14]. Another study by Sousa et al. (2021) developed structural models that reflect the mechanical, geometric, and material properties of precast RC industrial buildings in Portugal to derive fragility functions. Macro-elements were used to fully characterize the friction and dowel mechanisms at the critical column-beam joints of these structures. Considering the structural damage limit states, low seismic performance was identified even under low seismic demands [15]. Based on 273 precast industrial buildings selected from different regions of Türkiye, and considering the identified geometric and structural parameters, analytical-based fragility curves for 80 different structural models were presented as a function of spectral acceleration [16]. A study conducted by Ercolino et al. (2018) compared the collapse limit states through fragility curves for 40 single-story prefabricated reinforced concrete industrial building models designed according to the current Italian earthquake code. The fragility curves obtained by multi-stripe analyses performed through non-linear dynamic analyses are presented as a function of Sa [17].

Upon reviewing the literature, it is observed that fragility curves for single-story RC precast buildings are commonly presented as a function of Sa, PGA, and PGV [18-20]. The objective of this study is to develop analytically-based fragility curves for a typical RC precast industrial building using appropriate intensity measure parameters. To achieve this, a nonlinear dynamic analysis was conducted using the Incremental Dynamic Analysis (IDA) method with 50 earthquake ground motions that are spectrum-compatible. Fragility curves for four distinct damage states are presented as a function of Max Incremental Velocity (MIV), Housner Intensity (HI), Spectral Acceleration (Sa), Peak Ground Velocity (PGV), Modified Cordova Intensity (Sac*), and Velocity Spectrum Intensity (VSI).

3.1. Analytical-based fragility curves

The Incremental Dynamic Analysis (IDA) method has been employed for the development of fragility curves within the analytical framework [21]. This approach was primarily chosen to enable a comprehensive evaluation of advanced damage states across a wide range of seismic intensity levels. The fundamental steps for developing analytically-based fragility curves include: selecting appropriate ground motion records; performing analyses incrementally up to a defined upper level corresponding to the structure's dominant frequency; calculating the damage measure parameter value for each analysis result; repeating this process for all selected ground motions; and finally, deriving the fragility curves through a statistical evaluation of the relationship between the Engineering Demand Parameter (EDP) and the selected Intensity Measure (IM).

In this study, a representative single-story precast reinforced concrete (RC) industrial building is considered, consisting of two spans in the roof girder direction and six spans in the perpendicular direction, with all columns having cross-sectional dimensions of 45×45 cm. The selected structure, which sustained heavy damage during the earthquake, corresponds to a moderate-code design classification as defined by FEMA. Initially, a total of 1,245 nonlinear dynamic analyses were performed using 50 earthquake ground motion records. Subsequently, the correlation between the Maximum Drift Ratio (MDR) and the intensity measures—Max Incremental Velocity (MIV) (cm/sec), Housner Intensity (HI) (cm), Spectral Acceleration (Sa) (g), Peak Ground Velocity (PGV) (cm/sec), Modified Cordova Intensity (Sac*) (g), and Velocity Spectrum Intensity (VSI) (cm)—is illustrated in Figure 3.

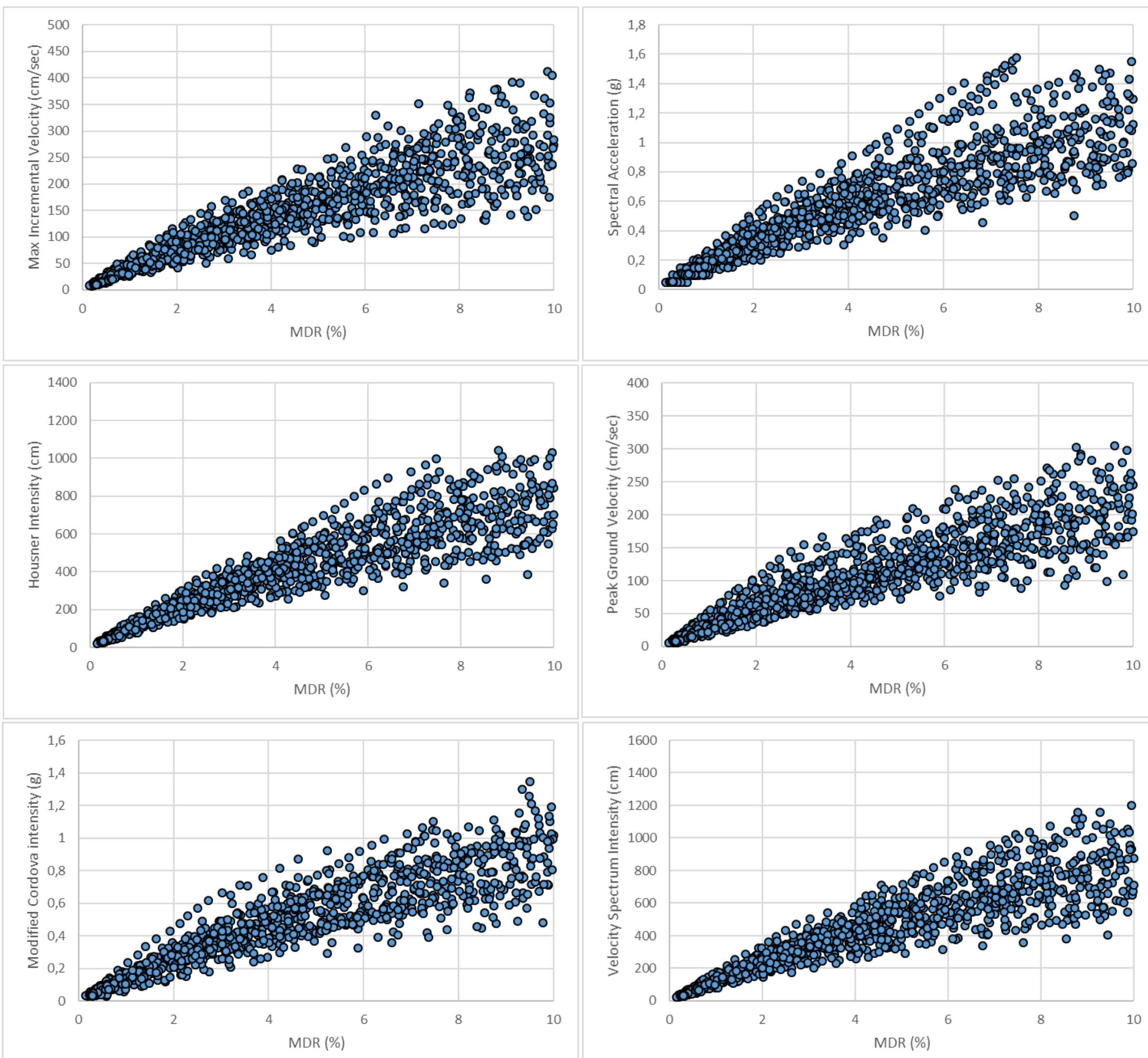

Figure 3. The dispersions of each EDP-IM pair.

The maximum drift ratio values as a damage parameter were calculated based on the damage index values (Park and Ang) proposed with reference to experimental studies. The threshold values corresponding to slight, moderate, extensive, and collapse damage states were considered as 1.2%, 2.5%, 4.2%, and 6.56%, respectively. Based on the distributions illustrated in Figure 3, fragility curves were developed for each intensity measure (IM) parameter, corresponding to four different damage states. The fragility curves developed as a function of the intensity measure (IM) parameters considered in the study are presented in Figure 4.

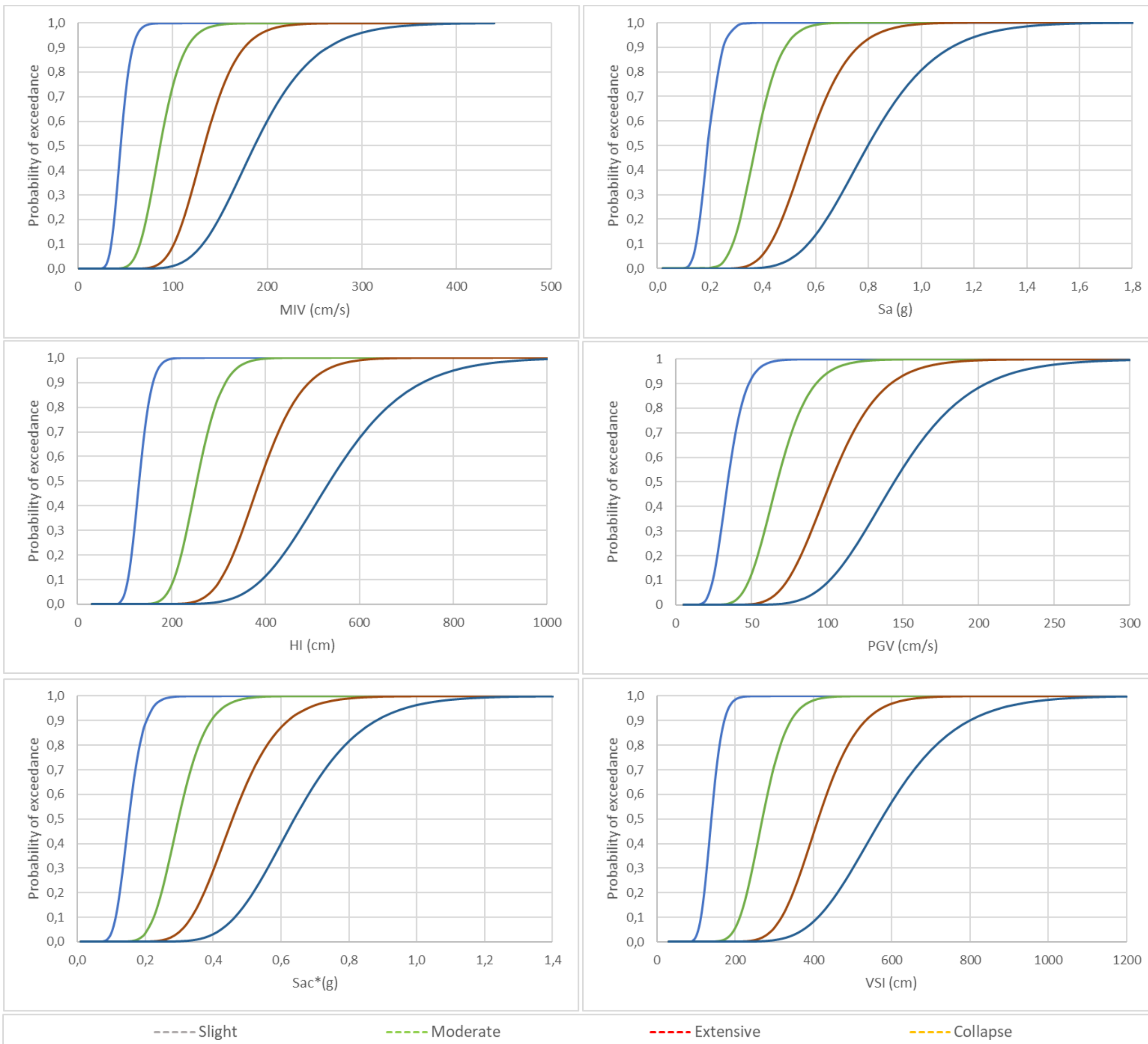

Figure 4. Analytically-based fragility curves for different IMs

As mentioned in the previous sections, fragility curves quantify the probability of exceeding a defined damage state given a specific intensity measure (IM) value. Accordingly, to enable a comparative assessment of the influence of different IM parameters on structural damage or economic loss, it is methodologically appropriate to evaluate their performance based on expected loss. To this end, Probable Maximum Loss (PML) values were computed for a representative single-story precast reinforced concrete (RC) structure using eight earthquake ground motion records, fragility curves, and the damage-to-loss functions provided by FEMA. The resulting PML values are presented in Figure 5.

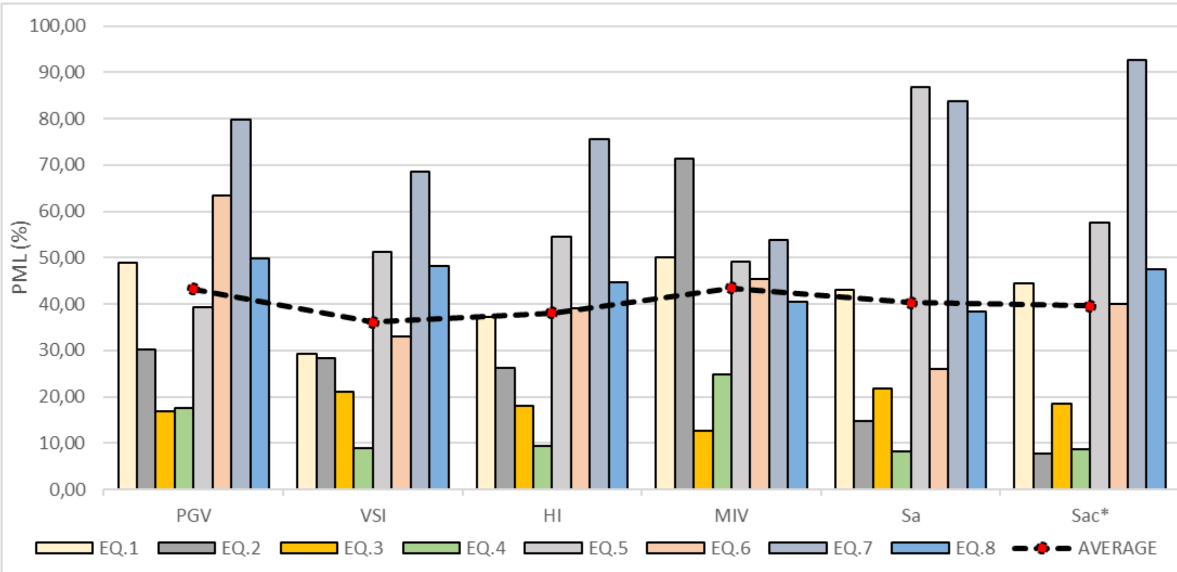

Figure 5. Calculated PML values for different IM parameters

As illustrated in Figure 5, the average Probable Maximum Loss (PML) values computed for the different intensity measure parameters exhibit consistency. The highest average PML value, 43.46%, was obtained for Max Incremental Velocity (MIV), while the lowest value, 36.08%, was computed for Velocity Spectrum Intensity (VSI). This study emphasizes that, with an appropriate classification of precast structures and the selection of suitable intensity measures (IM), it is possible to more accurately determine the relationship between seismic vulnerability analysis and the observed post-earthquake damage.

Conclusions

As a result of the Kahramanmaraş earthquakes, various types of structures, including single-story precast reinforced concrete (RC) buildings, experienced significant damage. In this study, the damaged structures were inspected on-site, and common damage types were identified. Notable observations included the formation of plastic hinges at the column-to-socket connections, the replacement of advanced plastic deformations with microcracks in columns with larger cross-sectional dimensions, visible plastic deformations (fractures) in the mid-span area of column elements, considerable damage to the connection elements, and damage to gussets.

Furthermore, a seismic vulnerability and risk assessment was conducted for a typical single-story precast RC structure that sustained significant damage following the earthquake. To this end, a set of 50 earthquake ground motion records was used, and nonlinear dynamic analyses were performed using the Incremental Dynamic Analysis (IDA) method. Based on the relationship between damage parameters and IMs, fragility curves were developed for the following parameters: Max Incremental Velocity, Housner Intensity, Spectral Acceleration, Peak Ground Velocity, Modified Cordova Intensity, and Velocity Spectrum Intensity.

In the final part of the study, Probable Maximum Loss (PML) calculations were made, and the effect of the considered intensity measure parameters on loss was examined. The calculated average PML values are internally consistent across the considered IMs. The highest average PML value is obtained for MIV, while the lowest is computed for VSI. This study demonstrates that by determining the appropriate intensity parameters for the considered structure class, comprehensive and accurate risk assessments can be conducted.

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