Development of analytical seismic fragility functions for the common buildings in Iran

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Abstract
One of the main components for developing regional seismic risk models is the fragility functions of common building types. Due to the differences between the national design codes, construction practices, and construction materials, it is necessary to develop specific fragility functions for the common building types which are constructed in each region. For this reason, the present study is devoted to filling this essential gap for Iran. Therefore, in the first step, the existing building types in the country are classified into 31 categories regarding material, lateral-load-resisting system, height, and code level. Also, by conducting comprehensive studies on all previously performed research in the country, structural and dynamic parameters have been collected for buildings in each class. This information was used to compute a large set of backbone curves for Iranian buildings taxonomy. Then nearly three hundred appropriate fragility functions were generated using non-linear time-history analyses on the generic backbone curves and a large set of ground motion records. Based on the existing empirical data from past earthquakes in the country, the validation of the resulting fragility functions was carried out. The resulted fragility functions can be utilized in seismic risk assessment studies in the country.

Keywords Earthquake · Iran · Iranian buildings · Taxonomy · Fragility functions · Seismic risk

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1 Introduction

Earthquake, as one of the most important natural disasters in Iran, has caused extensive economic and human losses, mainly due to the destruction of vulnerable buildings (Tavakoli and Ghaforiy-Ashtiany 1999). The most recent earthquake with Mw 7.3 occurred on November 12, 2017, in Sarpol-e Zahab city in Kermanshah province, which left approximately 600 fatalities (Zare et al. 2017). Reliable assessment of seismic vulnerability and risk of buildings requires the development of classified, reliable, and cogent fragility functions of the common building types constructed in Iran.

The development of appropriate/reliable fragility functions has been the aim of various studies. In these studies, fragility functions have been developed based on different methods, which can be classified into three main groups: empirical methods, expert opinion-based, and analytical methods. Empirical fragility functions are generated based on a statistical analysis of observed damage from past earthquakes, such as from data collected by post-earthquake surveys (Colombi et al. 2008; Sabetta et al. 1998). Expert opinion-based fragility functions are proposed based on the judgment and information of experts (ATC-13 1985; Jaiswal et al. 2012). Analytical fragility functions are developed starting from the statistical elaboration of damage distributions that are simulated from analyses of structural models under increasing earthquake intensity (HAZUS 1999; Ibarra and Krawinkler 2005; Rossetto and Elnashai 2005; Nasserasadadi et al. 2008; Samadian et al. 2019). Despite the existence of notable studies that have been conducted to develop fragility functions for different buildings in the country, due to the differences between the development methods, type of buildings, type of intensity measures, definition of damage states, the results of these studies are widely dispersed. Thus, it is necessary to develop uniform fragility functions for the common building types which are constructed in Iran.

This paper focused on a comprehensive study of the existing building types in the country to identify the common building types and building taxonomy of Iran based on the material, structural system, code conformance, and height, which resulted in 14 major types of buildings. Then, a comprehensive review was performed to determine the principal structural and dynamic characteristics of the 14 types of Iranian buildings to derive their equivalent Single-Degree-Of-Freedom (SDOF) models. For seismic demand, the presented method by Ghafoory-Ashtiany et al. (2021) was used in order to define representative Strong Ground Motion Records (SGMRs) from a large database of approximately 4000 records. Also, this paper has followed the analytical procedure proposed in Martins and Silva (2020) to develop fragility functions that consider the building-to-building variability, record-to-record variability, and uncertainty in the definition of the damage criterion using a low computational effort. All of the calculations were performed using the Vulnerability Modellers Toolkit (VMTK) (Martins et al. 2021). This study has developed more than 300 fragility functions for 14 common buildings in Iran, which have been considered in three code levels. The outcomes of this study can utilize in regional and national earthquake risk analyses.
2 A brief review of the current state of studies on the development of fragility functions for buildings

In the last decades, many important studies have been performed on the development of fragility functions worldwide [e.g., HAZUS (1999), Risk-UE project (Mouroux and Le Brun 2006), SYNER-G (Pitilakis et al. 2014), Global Earthquake Model (GEM) (Rossetto et al. 2014; D’Ayala et al. 2015), Silva et al. 2017, Villar-Vega et al. (2017), Martins and Silva (2020)]. Especially several studies have been performed to assess seismic fragility and vulnerability functions for Iranian buildings. The first study on seismic fragility curves in Iran was carried out by Tavakoli and Favakoli (1993) based on the Manjil-Rudbar earthquake data in 1990. This study presented empirical fragility functions for residential buildings regardless of the year of construction, seismic code, and building types. In another study, part of the GEM project was dedicated to the Middle East region, which was called the EMME project. The main part of the EMME project was relevant to seismic risk assessment in the region (Mansouri and Amini-Hosseini 2013). The first important result of this project was determining residential building taxonomy for Iran based on the national census database. The other significant result of this project was the derivation of appropriate vulnerability functions to estimate the building damage and the associated casualties.

Omidvar et al. (2012) have presented the empirical fragility curves for engineered steel and RC structures in Iran based on the observed damage from previous earthquakes that have occurred in Iran, mainly the 1990 Manjil and 2003 Bam earthquakes. Sadeghi et al. (2015) developed a set of vulnerability curves for the 42 Iranian building types by combining the existing fragility/vulnerability curves in Iran and other countries with similar seismicity and construction practices. Kazemi et al. (2017) developed fragility curves for steel braced frame structures using new spectral shape indicators and a weighted damage index in the city of Mashhad, Iran. Motamed et al. (2019) defined 23 building classes based on the construction material, building height, lateral load resisting system, and year of construction. The output of this study was the fragility functions of some of the building classes in Iran in order to utilize for the development of a probabilistic earthquake loss model for the country. Fallah Tafti et al. (2020) also categorized all buildings in Iran into 19 classes in terms of building structure types, building quality, and building height. In this study, 19 sets of expert judgment-based fragility functions were developed for the different types of common buildings in Iran. These fragility functions were developed using existing empirical fragility functions in Iran and those proposed for similar types of buildings in other countries. Kohrangi et al. (2021) classified the buildings into 27 classes based on age, height, material, and lateral-load-resisting system. This study developed a seismic risk model for the city of Isfahan using the exposure, fragility, and vulnerability models for the residential, mixed residential/commercial, and public building stock. Biglari et al. (2021) investigated the damaged database of engineered residential steel and RC buildings after Mw7.3 2017 earthquake. This study presented the empirical fragility curves for engineered steel and RC structures.
3 Building taxonomy in Iran

3.1 Development of a taxonomy for Iranian buildings

A necessary prerequisite for the vulnerability assessment of buildings is identifying the common building types in the country, which should be classified based on important parameters such as the construction material, the lateral load resisting system, design quality, and height. In order to develop and classify the comprehensive inventory of the most common building types in Iran, an extensive study has been performed on the existing building taxonomies worldwide to come up with an updated taxonomy for Iran with the consideration of the most important parameters [e.g., HAZUS (1999), RISK-UE project (Mouroux and Le Brun 2006), WHE-PAGER project (Jaiswal et al. 2010), Global Earthquake Model (Brzev et al. 2013)]. Also, similar studies have been conducted in Iran, which has been reviewed in the previous section. In addition to the mentioned studies, the Statistical Center of Iran (SCI 2018) Classified the existing buildings into three categories of steel structure, reinforced concrete, and others based on their structure types. These categories are not exhaustive and do not include all common buildings in Iran. Therefore, with respect to the description of several studies that were relevant for the development of a building taxonomy, in the current study, some parameters have been selected in order to classify existing buildings in urban and rural areas of Iran. These parameters consist of construction material, lateral load resisting system, code level (which is defined based on the integration of the seismicity level and the year of construction), and height. The procedure and the parameters that are reflected in the development of the building taxonomy are discussed in this section.

3.2 Building classification based on the construction material and the lateral load resisting system

In this section, based on previous research and the experts’ opinion, common building types in Iran are classified into two main categories: engineered buildings and non-engineered buildings. Engineered buildings are named as (1) Steel moment bare frames (S1_MRF); (2) Steel moment infill frame (S2_INFF); (3) Steel braced frame with the concrete shear wall (S3_MRF&CSW); (4) Steel braced frame (S4_SBR); (5) Steel frames with a dual system (S5_DUAL); (6) Steel braced frames with Khorjini connections (S6_SBR&KHC); (7) RC moment bare frame (C1_MRF); (8) RC moment infill frame (C2_INFF); (9) RC frames with the shear wall (C3_CSW); (10) RC tunnel-form (C4_TUF). Also, non-engineered buildings are named as (1) Confined masonry buildings (CM); (2) Unreinforced masonry buildings (UM); (3) Adobe (ADOBE), and (4) Wooden buildings (WD). The classification of Iranian buildings based on construction material and load resisting systems is presented in Table 1.

3.3 Buildings classification based on code level

In this study, code level is defined based on the year of construction and the seismicity levels of the region in which the buildings are designed. The existing Iranian buildings mainly were designed based on the various version of the Iranian standard for seismic
design of buildings (Standard No. 2800, ICSRDB 2014, http://www.std2800.ir) and the Iranian National Buildings Code parts 8, 9, and 10 (INBC Part 8 2013; INBC Part 9 2013; INBC Part 10 2013, https://inbr.ir). Therefore the existing buildings are categorized into four groups based on the different editions of Iranian building codes, as shown in Table 2.

The STD-2800 divided Iran into four seismic hazard zones with the Design-Based earthquake (DBE) values of 0.35 g (very high), 0.30 g (high), 0.25 g (moderate), 0.20 g (low). Due to the low differences in the reference design PGA, only two seismic levels were considered in this study. Level 1 is equivalent to low and moderate seismic zones, and
level 2 is equal to high and very high seismic zones of STD-2800. Combining the seismic
levels of the STD-2800 and the year of construction, common buildings in Iran are divided
into four code levels: Pre-Code, Low-Code (LC), Moderate-Code (MC), and High-Code
(HC). The classification of Iranian buildings based on the code level is presented in Fig. 1.
It should be noted that the code levels for the RC, Steel, and confined masonry buildings
are defined and named as 1. For Pre-Code and Low-Code levels have merged since their
differences are not recognizable and are named LC; 2. For Moderate-Code named as MC,
and 3. For High-Code named as HC. For unreinforced masonry, wood, and adobe build-
ings, these classifications based on code-level do not really exist, so only one level has been
considered for them.

### 3.4 Buildings classification based on height

Iranian building taxonomy, as shown in Table 3, has been defined based on the experts’
opinion of the IIEES Structural research center and the statistical survey on existing build-
ings in urban and rural regions of Iran. The height has been divided into three catego-
ries considering the different heights of buildings: Low-Rise (LR/1 to 3 storeys buildings),

| No. of edition | History of STD-2800, and national building codes | Iranian buildings classification based on the year of construction in this study |
|----------------|-------------------------------------------------|--------------------------------------------------------------------------------|
|                | National building codes                         |                                                                             |
|                | Part 10  | Part 9  | Part 8  |                                             |
| 1st edition    | 1986     | 1986    | 2005    | 1987 Prior to 1990                         |
| 2nd edition    | 2005     | 2006    | 2013    | 1999 1990–2006                             |
| 3rd edition    | 2008     | 2009    | –       | 2007 2006–2016                             |
| 4th edition    | 2013     | 2013    | –       | 2014 After 2016                            |

Fig. 1 Iranian buildings classification based on code-level
Table 3  Iranian buildings taxonomy and their descriptions and selected MBT in this study

| No. | Taxonomy          | Description                                      | N_{storey} | Range | MBT |
|-----|-------------------|--------------------------------------------------|------------|-------|-----|
| 1   | S1_MRF_LR         | Steel moment frames, low-rise                    | 1–3        | 2     |     |
| 2   | S1_MRF_MR         | Steel moment frames, mid-rise                    | 4–7        | 5     |     |
| 3   | S1_MRF_HR         | Steel moment frames, high-rise                   | +8         | 8     |     |
| 4   | S2_INFF_LR        | Steel infilled frames, low-rise                  | 1–3        | 2     |     |
| 5   | S2_INFF_MR        | Steel infilled frames, mid-rise                  | 4–7        | 5     |     |
| 6   | S2_INFF_HR        | Steel infilled frames, high-rise                 | +8         | 8     |     |
| 7   | S3_MRF&CSW_MR     | Steel frames with concrete shear walls, mid-rise | 4–7        | 5     |     |
| 8   | S3_MRF&CSW_HR     | Steel frames with concrete shear walls, high-rise| +8         | 8     |     |
| 9   | S4_SBR_LR         | Steel braced frame, low-rise                     | 1–3        | 2     |     |
| 10  | S4_SBR_MR         | Steel braced frame, mid-rise                     | 4–7        | 5     |     |
| 11  | S4_SBR_HR         | Steel braced frame, high-rise                    | +8         | 8     |     |
| 12  | S5_DUAL_LR        | Steel frames with dual system, low-rise          | 1–3        | 2     |     |
| 13  | S5_DUAL_MR        | Steel frames with dual system, mid-rise          | 4–7        | 5     |     |
| 14  | S5_DUAL_HR        | Steel frames with dual system, high-rise         | +8         | 8     |     |
| 15  | S6_SBR&KHC_LR     | Steel braced frames with Khorjini connections, low-rise | 1–3  | 2     |     |
| 16  | S6_SBR&KHC_MR     | Steel braced frames with Khorjini connections, mid-rise | 4–7 | 5     |     |
| 17  | C1_MRF_LR         | Reinforced concrete moment frames, Low-Rise      | 1–3        | 2     |     |
| 18  | C1_MRF_MR         | Reinforced concrete moment frames, Mid-Rise      | 4–7        | 5     |     |
| 19  | C1_MRF_HR         | Reinforced concrete moment frames, high-rise     | +8         | 8     |     |
| 20  | C2_INFF_LR        | Reinforced concrete infilled frame, low-rise     | 1–3        | 2     |     |
| 21  | C2_INFF_MR        | Reinforced concrete infilled frame, mid-rise     | 4–7        | 5     |     |
| 22  | C2_INFF_HR        | Reinforced concrete infilled frame, high-rise    | +8         | 8     |     |
| 23  | C3_CSW_MR         | Reinforced concrete frames with the concrete shear wall, mid-rise | 4–7 | 5     |     |
| 24  | C3_CSW_HR         | Reinforced concrete frames with the concrete shear wall, high-rise | +8 | 8     |     |
| 25  | C4_TUF_LR         | Reinforced concrete tunnel-form, low-rise        | 1–3        | 2     |     |
| 26  | C4_TUF_MR         | Reinforced concrete tunnel-form, mid-rise        | 4–7        | 5     |     |
| 27  | C4_TUF_HR         | Reinforced concrete tunnel-form, high-rise       | +8         | 8     |     |
| 28  | CM_LR             | Confined masonry buildings, low-rise             | 1–3        | 2     |     |
| 29  | UM_LR             | Unreinforced masonry buildings, low-rise         | 1–3        | 2     |     |
| 30  | WD_LR             | Wooden buildings, low-rise                       | 1–3        | 2     |     |
| 31  | ADOBE_LR          | Adobe buildings, low-rise                        | 1–3        | 2     |     |
Mid-Rise (MR/4 to 7 storeys buildings), and High-Rise (H.R./over 8 storeys buildings). Iranian buildings’ taxonomy and their related descriptions are described in Table 3.

4 Fragility analyses

Many studies using different methods have been conducted to develop fragility functions. The Global Earthquake Model (GEM) conducted a guideline, which has presented the most advanced methods for the derivation of robust fragility functions for the building typologies (D’Ayala et al. 2015). Similar researches were also conducted to describe existing methods for developing fragility curves and discuss the existing challenges in each of these methods (Calvi et al. 2006b; Silva et al. 2019). Utilizing these methodologies depends on the availability, quality, and level of precision of input data. In this study, the development of the fragility functions follows the analytical procedure proposed by Martins and Silva (2020). In this procedure, inputs are defined in terms of a set of ground motion records and equivalents SDOF systems that are illustrative of the buildings within each specific class. Structural responses have been obtained using Non-Linear Time-History Analysis (NLTHA) of equivalent SDOF systems with the consideration of record-to-record uncertainty and building-to-building variability. Then the fragility functions have been developed using the cloud analysis approach proposed by (Jalayer et al. 2015), considering the uncertainty in the definition of the damage criterion. All of the calculations related to the non-linear response of the SDOF oscillators and the derivation of fragility functions were performed using the VMTK (Martins et al. 2021), open-source software for deriving fragility and vulnerability functions. One of the advantages of this procedure is utilizing the simplified SDOF models, which their response is not computationally heavy and time-consuming. All of the required inputs and steps for the development of the fragility functions are defined separately and entirely in the following sub-sections. Also, each of the above-mentioned steps is explained in the flow diagram presented in Fig. 2.

4.1 Definition of structural and dynamic parameters for Iranian buildings

In this section, to define the proper structural parameters required for the capacity curves of each building class, a review has been accomplished on the previous research conducted by Calvi (1999), Borzi et al. (2008a, b), Ahmad et al. (2010), Villar-Vega et al. (2017), and Martins and Silva (2020). The selected parameters are shown in Table 4. In this study, initially, the backbone curves from the existing studies in Iran were collected to define the structural and dynamic parameters for Iranian buildings classes. For some of the building types where not sufficient data were available in Iran, the parameters were chosen based on the existing studies which have similar buildings to Iran. Finally, approximately 100 backbone curves were collected. A weight factor was assigned for each curve considering the expert’s opinion about the level of appropriateness and accuracy of different researches collected in this survey. Then, the existing parameters in each category were combined, based on their weights obtained from engineering judgment, to determine the final parameters for each class of building. The considered structural and dynamic parameters for Iranian building classes and the list of related references, which have been utilized to define these parameters, are demonstrated in Table 4.
4.2 Nonlinear equivalent SDOF systems for the buildings taxonomy

One generic capacity curve per building class in Acceleration Displacement Response Spectrum (ADRS) format (spectral acceleration versus spectral displacement) is defined.
| Building class | Description                           | $T_y$ [s] | $N_{storey}$ | Inter-storey height [m] | Yield drift [%] | Ult. drift [%] | $\Gamma$ | References                                                                 |
|----------------|----------------------------------------|-----------|--------------|------------------------|----------------|---------------|---------|----------------------------------------------------------------------------|
| S1_MRF_LC      | Steel moment frames, low-code          | $0.091 \times H^{0.8}$ | 1–10        | 3.0–3.2                | 0.55           | 2.7           | 1.35    | Tavakoli and Rashidi Alashti (2013), Amiri et al. (2012), Mohsenian et al. (2020a), Haj Najafi and Tehranizadeh (2013), Martins and Silva (2020), Beiranvand (2017), Mobarrez Chini Belagh (2016), Entezari Zarch (2017), Poursha et al. (2011), Mehdizadeh and Karamodin (2017), Namjouyan (2013), Tehranizadeh and Yakhchalian (2011), Rahmani et al. (2018) |
| S1_MRF_MC      | Steel moment frames, mid-code          | $0.091 \times H^{0.8}$ | 1–10        | 3.0–3.2                | 0.65           | 3.7           | 1.35    | S1_MRF_HC                                                                   |
| S1_MRF_HC      | Steel moment frames, high-code         | $0.091 \times H^{0.8}$ | 1–10        | 3.0–3.2                | 0.75           | 4.7           | 1.35    |                                                                                          |
| S2_INFF_LC     | Steel infilled frames, low-code        | $0.06 \times H^{0.75}$ | 1–10        | 3.0–3.2                | 0.38           | 1.5           | 1.35    | Nassirpour and D’Ayala (2014), Kazemi et al. (2017), Martins and Silva (2020), STD-2800 version 4 (ICSRDB 2014), Lookzadeh (2020) |
| S2_INFF_MC     | Steel infilled frames, mid-code        | $0.06 \times H^{0.75}$ | 1–10        | 3.0–3.2                | 0.43           | 1.8           | 1.35    | S2_INFF_HC                                                                  |
| S2_INFF_HC     | Steel infilled frames, high-code       | $0.06 \times H^{0.75}$ | 1–10        | 3.0–3.2                | 0.50           | 2             | 1.35    |                                                                                          |
| S3_MRF&CSW_LC  | Steel frames with concrete shear walls, low-code | $0.053 \times H^{0.75}$ | 4–10        | 3.0–3.2                | 0.25           | 1.1           | 1.35    | Esmaeili et al. (2013), Martins and Silva (2020), Kazemi et al. (2013), Rahmani Qeranqayah (2014), Raji (2012) |
| S3_MRF&CSW_MC  | Steel frames with concrete shear walls, mid-code | $0.053 \times H^{0.75}$ | 4–10        | 3.0–3.2                | 0.4            | 1.3           | 1.35    | S3_MRF&CSW_HC                                                              |
| S3_MRF&CSW_HC  | Steel frames with concrete shear walls, high-code | $0.053 \times H^{0.75}$ | 4–10        | 3.0–3.2                | 0.55           | 1.5           | 1.35    |                                                                                          |
| Building class | Description | \( T_y \) [s] | \( N_{\text{storey}} \) | Inter-storey height [m] | Yield drift [%] | Ult. drift [%] | \( I' \) | References |
|----------------|-------------|----------------|----------------|----------------------|----------------|--------------|--------|-----------|
| S4L\_SBR\_LC  | Steel braced frame, low-code | \( 0.072 \times H^{0.8} \) | 1–10 | 3.0–3.2 | 0.75 | 2 | 1.35 | Nassipour and D'Ayala (2014), Dorri et al. (2019), Heidari et al. (2010), Haj Najafi and Tehranizadeh (2013), Martins and Silva (2020), Mahmoudi and Zaree (2011), Mahmoudi and Zaree (2012) Mahmoudi and Zaree (2013), Jahangir and Karamodin (2015), Pourmoghadam (2017), Etezadi Ghozhdi (2012), Dolatshahi et al. (2018) |
| S4L\_SBR\_MC  | Steel braced frame, mid-code | \( 0.072 \times H^{0.8} \) | 1–10 | 3.0–3.2 | 0.79 | 2.6 | 1.35 |
| S4L\_SBR\_HC  | Steel braced frame, high-code | \( 0.072 \times H^{0.8} \) | 1–10 | 3.0–3.2 | 0.83 | 3.2 | 1.35 |
| S5\_DUAL\_LC  | Steel frames with dual system, low-code | \( 0.07 \times H^{0.8} \) | 1–10 | 3.0–3.2 | 0.88 | 1.8 | 1.35 | Nassipour and D'Ayala (2014), Gerami et al. (2013), Maddah and Eshghi (2018), Kalani Sarokolayi et al. (2015), STD-2800 version 4 (ICSRDB 2014), STD-2800 version 2 (ICSRDB 1999), Hosseini Hashemi and Hassanzadeh (2008), Hosseini Hashemi and Ghafoory-Ashtiany (2002) |
| S5\_DUAL\_MC  | Steel frames with dual system, mid-code | \( 0.07 \times H^{0.8} \) | 1–10 | 3.0–3.2 | 0.93 | 2.2 | 1.35 |
| S5\_DUAL\_HC  | Steel frames with dual system, high-code | \( 0.07 \times H^{0.8} \) | 1–10 | 3.0–3.2 | 0.98 | 2.6 | 1.35 |
| S6\_SBR&KHC\_LC | Steel braced frames with Khorjini connections, low-code | \( 0.06 \times H^{0.75} \) | 1–7 | 3.0–3.2 | 0.2 | 0.7 | 1.4 | Kiani et al. (2016), STD-2800 version 4 (ICSRDB 2014), STD-2800 version 2 (ICSRDB 1999), Hosseini Hashemi and Hassanzadeh (2008), Hosseini Hashemi and Ghafoory-Ashtiany (2002) |
| S6\_SBR&KHC\_MC | Steel braced frames with Khorjini connections, mid-code | \( 0.06 \times H^{0.75} \) | 1–7 | 3.0–3.2 | 0.25 | 0.85 | 1.4 |
| Building class | Description | $T_y$ [s] | $N_{storey}$ | Inter-storey height [m] | Yield drift [%] | Ult. drift [%] | $\Gamma$ | References |
|---------------|-------------|----------|--------------|-------------------------|----------------|--------------|--------|------------|
| C1_MRF_LC     | RC moment frames, low-code | $0.1 \times H$ | 1–10 | 3.0–3.2 | 0.72 | 1.5 | 1.4 | Mahdi and Soltangharaei, (2011), Mahdi (2009), Khoshnoud (2010), Khoshnoudian et al. (2011), Khoshnoud and Marsono (2011), Martins and Silva (2020), Villar-Vega et al. (2017), Gholizad and Safari (2014), Kalantari et al. (2020), Hosseini et al. (2019), Mortezaei and Ronagh (2013) |
| C1_MRF_MC     | RC moment frames, mid-code | $0.1 \times H$ | 1–10 | 3.0–3.2 | 0.76 | 2.5 | 1.4 |
| C1_MRF_HC     | RC moment frames, high-code | $0.1 \times H$ | 1–10 | 3.0–3.2 | 0.78 | 3.5 | 1.4 |
| C2_INFF_LC    | Reinforced concrete infilled frame, low-code | $0.060 \times H$ | 1–10 | 3.0–3.2 | 0.25 | 1.3 | 1.4 | Martins and Silva (2020), Villar-Vega et al. (2017), STD-2800 version 4 (ICSRDB 2014), Khoshnoud and Marsono (2011), Erberik (2008b), Crowley and Pinho (2004), Crowley and Pinho (2009), Borzi et al. (2008b) |
| C2_INFF_MC    | Reinforced concrete infilled frame, mid-code | $0.054 \times H$ | 1–10 | 3.0–3.2 | 0.35 | 1.6 | 1.4 |
| C2_INFF_HC    | Reinforced concrete infilled frame, high-code | $0.048 \times H$ | 1–10 | 3.0–3.2 | 0.45 | 1.9 | 1.4 |
| C3L_CSW_LC    | RC frames with shear wall, low-code | $2 \times (0.049 \times N)$ | 4–10 | 3.0–3.2 | 0.24 | 1.0 | 1.4 | Martins and Silva (2020), Villar-Vega et al. (2017), Hassan and Jafari (2012), Motamed et al. (2019), Aliabadi (2016), Tavakoli (2016) |
| C3L_CSW_MC    | RC frames with shear wall, mid-code | $2 \times (0.048 \times N)$ | 4–10 | 3.0–3.2 | 0.27 | 1.2 | 1.4 |
| C3L_CSW_HC    | RC frames with shear wall, high-code | $2 \times (0.047 \times N)$ | 4–10 | 3.0–3.2 | 0.3 | 1.4 | 1.4 |
| C4_TUF_LC     | RC tunnel-form, low-code | $0.07 \times H^{0.75}$ | 1–10 | 3.0–3.2 | 0.4 | 0.9 | 1.4 | Ashkoo (2015), Shokrollahi Yancheshmeh (2014), Mohsenian et al. (2021), Mohsenian et al. (2020b) STD-2800 version 4 (ICSRDB 2014) |
| C4_TUF_MC     | RC tunnel-form, mid-code | $0.07 \times H^{0.75}$ | 1–10 | 3.0–3.2 | 0.45 | 1.1 | 1.4 |
| C4_TUF_HC     | RC tunnel-form, high-code | $0.07 \times H^{0.75}$ | 1–10 | 3.0–3.2 | 0.5 | 1.3 | 1.4 |
| Building class | Description | $T_y$ [s] | $N_{storey}$ | Inter-storey height [m] | Yield drift [%] | Ult. drift [%] | $\Gamma$ | References |
|----------------|-------------|-----------|--------------|------------------------|----------------|---------------|--------|------------|
| CM_LC          | Confined masonry buildings, low-code | $0.060 \times H^{0.9}$ | 1–3 | 2.8–3.0 | 0.18 | 0.6 | 1.5 | Martins and Silva (2020), Lotfy et al. (2019), Hamzeh et al. (2018), Riahi et al. (2009), Ahmad et al. (2010), Sartaji et al. (2017) |
| CM_MC          | Confined masonry buildings, mid-code | $0.058 \times H^{0.9}$ | 1–3 | 2.8–3.0 | 0.20 | 0.66 | 1.5 | |
| CM_HC          | Confined masonry buildings, high-code | $0.056 \times H^{0.9}$ | 1–3 | 2.8–3.0 | 0.22 | 0.72 | 1.5 | |
| UM             | Unreinforced masonry buildings | $0.062 \times H^{0.9}$ | 1–3 | 2.8 | 0.10 | 0.40 | 1.4 | Villar-Vega et al. (2017), Calvi (1999), Erberik (2008a), Bal et al. (2008), Borzi et al. (2008a), Shabani et al. (2021), Ranjbaran et al. (2012) |
| WD             | Wooden buildings | $0.75 \times (0.066 \times H^{0.9} + 0.25 \times (0.123 \times H^{0.5}))$ | 1–3 | 2.5 | 0.16 | 1.19 | 1.4 | Villar-Vega et al. (2017), Martins and Silva (2020), Camelo et al. (2002), Goda (2015) |
| Adobe          | Adobe buildings | $0.066 \times H^{0.9}$ | 1–3 | 2.6 | 0.08 | 0.35 | 1.4 | Martins and Silva (2020), Tarque et al. (2012), Preciado et al. (2020) |

$N_{storey}$ correspond to the number of storeys, $H_{storey}$ corresponding to the typical building storey height, $T_1$ is the oscillator period, $T_y$ corresponding to the period of vibration at the yielding point, $\Gamma$ represents the first mode of vibration participation factor adopted.

$\theta_y$ [or Yield drift (%)] represents the global drift at the yielding point of the Multi-Degree-of-Freedom (MDOF) structure.

$\theta_u$ [or Ult. drift (%)] represents the global drift at the ultimate point of the MDOF structure.
based on the parameters determined in the previous section. The elastic-perfectly plastic behavior of each SDOF oscillator is computed based on the related backbone curve in ADRS format using the following equations:

$$S_d = \frac{N_{\text{Storey}} \times H_{\text{storey}} \times \theta_{\text{global}}}{\Gamma}, \quad S_{\text{ay}} = S_{\text{dy}} \times \left(\frac{2 \times \pi}{T_y}\right)^2, \quad S_{\text{au}} = S_{\text{ay}}$$  \hspace{1cm} (1)

where, $S_d$ = spectral displacement at the yielding or ultimate points, depending on the global drift $\theta_{\text{global}}$, $N_{\text{Storey}}$ = the number of storeys, $H_{\text{storey}}$ = the inter-storey height, $\Gamma$ = first mode of vibration participation factor; $T_y$ stands for the period of vibration at the yielding point; and $S_{\text{ay}}$ and $S_{\text{au}}$ represents the spectral acceleration at the yielding and ultimate points, respectively. In order to characterize the seismic response and the performance of each building type, a generic equivalent SDOF system with a backbone curve and a hysteresis behavior are defined. For this purpose, recommendations by Dolšek and Fajfar (2008), Riahi et al. (2009), Bal et al. (2010), Silva et al. (2014b), Villar-Vega et al. (2017), Martins and Silva (2020), and also the experts’ opinions have been used. The “Bilinear idealization shape” was supported to express the backbone curve for the steel and timber structures, which define based on three pairs of points, as illustrated in Fig. 3a. As depicted in Fig. 3a, the first point of the backbone curve was equal to zero. The last two points of the backbone curve were calculated according to the yield displacement ($S_{\text{dy}}$), the ultimate displacement ($S_{\text{du}}$), and the corresponding spectral accelerations ($S_{\text{ay}}, S_{\text{au}}$).

The backbone curves with three branches can also be found in the literature, depending on the characteristics of the building type. The “Tri-linear idealization shape” was supported to express the backbone curve for the RC, confined and unreinforced masonry, and adobe structures. Tri-linear backbone curves are defined based on four pairs of points as described in Fig. 3b. In these curves, the initial branch has been defined with two different slopes. The first is proportional to the elastic period ($T_1$), and the second is proportional to the yielding period ($T_y$). In this case, the value of $T_y$ is considered equal to 1.5 times the value of $T_1$ (Calvi et al. 2006a; Crowley and Pinho 2006; Martins and Silva 2020). The displacements for these building classes were defined based on the yield and ultimate displacements ($S_{\text{dy}}, S_{\text{du}}$).

Martins and Silva (2020) recommended the “Quadrilinear idealization shape” to represent the backbone curve for the infilled reinforced concrete structures that are anticipated a notable decrease in the strength and stiffness due to the structural damage of the masonry walls, as shown in Fig. 3c. These curves are defined through the yield ($S_{\text{dy}}$) and ultimate ($S_{\text{du}}$) displacements and the elastic ($T_1$) and yield ($T_y$) periods. The displacements for the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3a.png}
\caption{(a) Generic two-lines backbone curve, (b) Generic Tri-lines backbone curve, (c) backbone curves of bare frame vs infilled frames}
\end{figure}
first two points were defined similarly to the tri-linear backbone curve. The corresponding spectral acceleration for the first two points was considered equal to 50 percent of the spectral acceleration at the yielding point ($0.5 S_{ay}$) and the spectral acceleration at the yielding point ($S_{ay}$), respectively. The third point corresponds to the yielding point of the RC frame alone, without any contribution to the infills (i.e., bare frame). In the end, the last point is defined based on the ultimate displacement of the system.

4.3 Selection of ground motion records

Generally, the GM selection methods that are utilized for seismic vulnerability assessment of structures can be divided into two main categories. In the first method, a more general approach is used to select generic sets of ground motions in order to investigate the structure’s responses. These sets of ground motions are popular because they allow users to obtain ground motions with a minimum amount of effort. These sets of ground motion records are appropriate for vulnerability assessment because they simplify the assessment procedure. In the second method, the ground motion records select to represent the seismic hazard in the specific site. These sets of ground motions are viewed as the best estimate of what future ground motions are at the particular site of interest (Baker et al. 2011; Ghafory-Ashtiany et al. 2011, 2014; Jayaram et al. 2011; Baker 2011; Mousavi et al. 2011; Azarbakht et al. 2012; Silva et al. 2019; Mohandesi et al. 2019).

This study aims to develop a national database of fragility functions to be used in large-scale risk assessments all over the country. So, the records have been selected utilizing the first aforementioned method considering the tectonic environment and seismicity of Iran. So, an extensive database of ground motions has been specially selected from the IIEES SGMR Toolbox (Ghafory-Ashtiany et al. 2021) to be used to perform NLTHAs on the idealized SDOF systems. Using this extensive database of ground motion records helps to consider the record-to-record variability, which is one of the significant sources of uncertainty in fragility assessment. IIEES SGMR toolbox includes records from 1975 to 2017, as shown in Fig. 4a. Most of the earthquakes and recorded data belong to the years 2005, 2006, 2012, 2013, and 2017. This main dataset is composed of 3521 time-series out of 1025 earthquakes recorded at 594 different stations,
with moment magnitudes varying from 2.0 to 7.7 and Joyner-Boore distances within 220 km. Figure 4b demonstrates the location of considered stations and the location of the selected earthquakes in Iran. Most of the data (about 89%) are relative to distances shorter than 60 km, and most of the stations are V_s30 larger than 375 m/s (using the V_s30 measured or estimated by the empirical method).

Finally, in this study, PGA and spectral acceleration (SA) at three periods of vibration (0.3 s, 0.6 s, and 1.0 s) were selected as the Intensity Measure (IM) for the fragility assessment. These Intensity Measure Types (IMT) were utilized during the record selection procedure in order to have four sets of records close to the dynamic properties of the building types, which increase the accuracy and efficiency in response prediction. Ten levels of ground shaking were defined for each intensity measure type between 0.1 g and 2.0 g. Then, for each Intensity Measure Level (IML), 30 records were randomly selected at each level of ground shaking from the initial catalog. In case 30 records have not existed for a particular IML (which generally occurs in high IML), the records were scaled up to a maximum of 2.0 times (Watson-Lamprey and Abrahamson 2006) to lead to the minimum number of ground motion records. Figure 5 illustrates the response spectra of a set of 300 ground motion records corresponding to each of four selected IM types.

Fig. 5 Response spectra of the selected ground motion records considering: a PGA, b Sa (0.3 s), c Sa (0.6), and d Sa (1)
4.4 Definition of the damage criterion

There are several classifications of damage criteria to describe building damage from different perspectives (e.g., ATC-13 1985; HAZUS 1999). In this study, four damage criteria are considered, corresponding to slight, moderate, extensive, and complete damage levels following the recommendations of previous studies (Lagomarsino and Giovinazzi 2006; Silva et al. 2014a; Villar-Vega et al. 2017; Martins and Silva 2020). These Limit states are defined based on the yielding and ultimate displacement of each system. Herein, the limit states corresponding to specified damage criteria for this study have been described in the following list:

(i) Slight Damage (LS1) corresponds to 75 percentile of spectral displacement at the yielding point;
(ii) Moderate Damage (LS2), defined at spectral values of $0.5 \times S_{dy} + 0.33 \times S_{du}$;
(iii) Extensive Damage (LS3), defined at spectral values of $0.25 \times S_{dy} + 0.67 \times S_{du}$;
(iv) Complete damage (LS4), equal to spectral displacement at the ultimate point;

The Engineering Demand Parameter (EDP) for each damage criteria was fitted with a lognormal distribution for this study. The statistical parameters assigned to this lognormal distribution were a mean equal to the threshold presented above and a coefficient of variation of 45% (Dymiotis et al. 1999, Borzi et al. 2008a, b; Martins and Silva 2020).

4.5 Fragility functions assessment methodology

As briefly described earlier, all calculations relevant to the development of fragility functions (e.g., derivation of the backbone curves, structural response) are performed by the VMTK software (Martins et al. 2021). The VMTK is an open-source software developed with the Python programming language and integrated with the open-source finite element model software OpenSEES (McKenna et al. 2000) in order to compute the non-linear response of the SDOF oscillators. The VMTK’s source code is freely available through a public GitHub repository (https://github.com/GEMScienceTools/VMTK-Vulnerability-Modellers-ToolKit). This software consists of six modules that users can perform all the steps of developing fragility and vulnerability curves from the record selection to the validation and verification of the results utilizing the VMTK. These modules are:

(i) Selection of appropriate ground motion records in order to take into consideration the record-to-record uncertainty,
(ii) Definition of structural capacity that is defined by bilinear, trilinear or quadrilinear backbone curves,
(iii) Structural response module,
(iv) Fragility function module,
(v) Derivation of vulnerability functions,
(vi) Validation of the results,

This section gives an overview of modules (iii) and (iv). Module (iii) estimates structural response by utilizing Nonlinear Dynamic Analyses (NDA) on SDOF oscillators using OpenSEES software. The hysteresis model of each SDOF was defined according to the relevant
backbone curve and using the uniaxial material Pinching4 considering structural degradation in three stages: (1) unloading stiffness degradation, (2) reloading stiffness degradation, and (3) strength degradation. The default degradation implementation, which was adapted from simpleSDOF4.tcl by Vamvatsikos (2011), utilizes the energy option of Pinching4 (The reader is encouraged to study Martins et al. (2021) for more information about this process). In the present study, a damping ratio equal to 7.5% is considered for masonry and adobe buildings, 5% for RC building classes, and 2% for steel and wooden constructions. Each SDOF system (one per building class) was tested against a set of ground motion records, leading to 300 dynamic analyses. After performing the structural analyses, the maximum spectral displacement or the maximum spectral acceleration was computed for each SDOF as the EDPs.

In module (iv), the development of the fragility functions is performed based on the cloud analysis presented by Jalayer et al. (2015). Cloud analysis is based on simple regression between the structural response and the seismic intensity measure for a suit set of ground motion records in the logarithmic space. With a proper record selection, the cloud method manages to consider both record-to-record variability and building-to-building variability, which are two main sources of uncertainty related to the fragility analysis. Figure 6a shows a distribution of EDPs versus Intensity Measure (IM) levels for a 5-storey steel moment frame building. So, the expected value of the EDP for an intensity measure \( E[\ln (EDP_i)] \) is modeled by a linear regression equation with parameters a and b, while the standard error of the regression estimates the standard deviation or dispersion due to the record-to-record variability (\( \sigma_{rec-to-rec} \)); Eq. (2). In this equation, \( E[\ln (EDP_i)] \) stands for the expected value of the EDP given an IM, \( \sigma_{rec-to-rec} \) is the record-to-record variability, b and a are the regression parameters, n is the number of records, and EDP\(_i\) corresponds to the i-EDP value obtained from the non-linear analysis for the corresponding IM\(_i\).

\[
E[\ln EDP] = \ln a + b \ln IM
\]

\[
\sigma_{rec-to-rec} = \sqrt{\frac{\sum_{i=1}^{n} (\ln EDP_i - E[\ln EDP])^2}{n - 2}}
\]

Fig. 6  a Scatter of ln (EDP) and ln (IM) with Curve Fitting using Linear Regression, b Scatter of ln (EDP) and ln (IM), with the associated best-fit uncensored and censored regressions
From the two regression models (linear and censored) analysis, censored regression, where the structural responses are unexpectedly high, has been used to prevent significant bias in the fragility functions. The parameters of the best-fit curve (a and b) in the linear regression analysis (considering all observations) compute utilizing the Maximum Likelihood Method (MLE) (Lallemant et al. 2015; Stafford 2008), by the Eq. (3). In the following equation, $\phi$ stands for the probability density function of the standard Gaussian distribution.

$$L = \prod_{i=1}^{n} \left[ \phi \left( \frac{EDP_i - a - bIM_i}{\sigma} \right) \right]$$

A factor equal to 1.5 has been determined for censored regression analysis (Schnedler 2005), representing the ratio between maximum allowable EDP and the last limit state (e.g., Complete). Considering this certain threshold ($EDP_c = 1.5 \times EDP$), the observed data (i.e., $EDP_i$) is divided into two categories: the uncensored ($n_u$) and the censored ($n_c$) observations. A step-by-step description of this process (with or without the censored regression) can be found in (Martins and Silva, 2020). Figure 6b depicted these data points using circles and squares, respectively, for a 5-storey steel moment frame structure. For the censored regression analysis (e.g., Stafford 2008), the following equation has been utilized, where $\Phi$ stands for the cumulative function of the standard Gaussian distribution:

$$\ln(L) = \sum_{j=1}^{n_c} \left( 1 - \Phi \left( \frac{EDP_c - a - bIM_j}{\sigma} \right) \right) + \sum_{j=1}^{n_0} \left[ \ln \Phi \left( \frac{EDP_j - a - bIM_j}{\sigma} \right) \right]$$

As mentioned earlier, the two types of uncertainty which exist in fragility analysis are as follows:

- $\sigma_{rec-to-rec}$, which corresponds to record-to-record variability, has been considered by employing a large set of ground motion records.

- $\sigma_{building-to-building}$ corresponds to building-to-building variability, which can be considered in two different methods according to Martins and Silva (2020). The first method is to consider a large number of numerical models (backbone curves) per building class (Erberik 2008a, b; Villar-Vega et al. 2017). The second method is to increase the standard deviation directly, which decreases the volume and time of needed computations. In this study, a value of 0.3 has been considered as the building-to-building variability. So, assuming $\sigma_{rec-to-rec}$ and $\sigma_{building-to-building}$, the total uncertainty ($\sigma_{total}$) is computed according to Eq. (5).

$$\sigma_{total} = \sqrt{\left(\sigma_{rec-to-rec}\right)^2 + \left(\sigma_{building-to-building}\right)^2}$$

So the fragility function developed based on the Cloud analysis can be expressed as Eq. (6):

$$P[LS \geq lsi | IM] = \phi \left( \frac{\ln EDP_{lsi} - E[\ln EDP][\ln IM]}{\sigma_{total}} \right)$$

In the aforementioned equation, ($P[LS \geq lsi | IM]$) is the probability of exceeding a certain limit state for a given intensity measure, and $EDP_{lsi}$ is the engineering demand parameter (i.e., maximum displacement) for limit state $lsi$. As previously mentioned, the engineering demand parameters corresponding to each damage criteria were fitted to a lognormal distribution in order to consider another source of uncertainty corresponding.
to the definition of damage criteria. So, with regard to this source of uncertainty, the fragility functions were defined by the following equation:

$$P[LS \geq l_{Si}|IM] = \sum_{j=1}^{n} \phi \left( \frac{lnEDP_{lsi,j} - E[lnEDP|lnIM]}{\sigma_{total}} \right) \cdot P[EDP_{lsi,j}]$$  \hspace{1cm} (7)

In the above equation, $P[EDP_{lsi,j}]$ stands for the probability of occurrence of $EDP_{lsi,j}$, and $EDP_{lsi,j}$ is an increment of the possible range of EDPs for damage state $lsi$. The steps followed for the fragility assessment using cloud analysis are illustrated in Fig. 7, while the probability of exceedance for three Intensity Measure Levels (IMLs) given a considered Limit State ($LS_i$) is illustrated in the left panel of Fig. 7. The hatched area under the probability density functions illustrated in the left panel presented the probability of exceeding $LS_i$ for three IMLs. The resulting probability of $LS_i$ for three IMLs is plotted as data points on the right panel.

For the purpose of this study, four types of intensity measures have been considered in fragility analysis. These intensity measures were selected based on the yield period of each building type. The fragility functions have been produced for 1–10 storeys for each building type. More than 300 fragility functions have been developed for 14 common buildings in Iran. In order to present the results briefly in the paper, a Model Building Type (MBT) has been considered for each building class. Table 5 describes the considered IDs for each MBTs and a detailed description of them. Table 5 presents an example of defining Labels for each building class; these labels are used to display fragility function results for each building type in Sect. 5. Likewise, the label related to other building classes is defined similarly to Table 5. The developed fragility functions for other building classes are available by request from the corresponding author.

![Fig. 7 A schematic of the fragility assessment based on the cloud analysis approach: a probability of exceedance for three IMLs given a limit State; b fragility function for a given limit State](image-url)
Table 5  Selected MBT in this study and their descriptions

| Model building type | Description |
|---------------------|-------------|
| S1_MRF_LC/H:2,5,8   | Steel moment frames, low-code/height: 2, 5, and 8 storeys |
| S1_MRF_MC/H:2,5,8   | Steel moment frames, mid-code/height: 2, 5, and 8 storeys |
| S1_MRF_HC/H:2,5,8   | Steel moment frames, high-code/height: 2, 5, and 8 storeys |
| S2_INFF_LC/H:2,5,8  | Steel infilled frames, low-code/height: 2, 5, and 8 storeys |
| S2_INFF_MC/H:2,5,8  | Steel infilled frames, mid-code/height: 2, 5, and 8 storeys |
| S2_INFF_HC/H:2,5,8  | Steel infilled frames, high-code/height: 2, 5, and 8 storeys |
| S3_MRF&CSW_LC/H:5,8 | Steel frames with concrete shear walls, low-code/height: 5 and 8 storeys |
| S3_MRF&CSW_MC/H:5,8 | Steel frames with concrete shear walls, mid-code/height: 5 and 8 storeys |
| S3_MRF&CSW_HC/H:5,8 | Steel frames with concrete shear walls, high-code/height: 5 and 8 storeys |
| S4_SBR_LC/H:2,5,8   | Steel braced frame, low-code/height: 2, 5, and 8 storeys |
| S4_SBR_MC/H:2,5,8   | Steel braced frame, mid-code/height: 2, 5, and 8 storeys |
| S4_SBR_HC/H:2,5,8   | Steel braced frame, high-code/height: 2, 5, and 8 storeys |
| S5_DUAL_LC/H:2,5,8  | Steel frames with dual system, low-code/height: 2, 5, and 8 storeys |
| S5_DUAL_MC/H:2,5,8  | Steel frames with dual system, mid-code/height: 2, 5, and 8 storeys |
| S5_DUAL_HC/H:2,5,8  | Steel frames with dual system, high-code/height: 2, 5, and 8 storeys |
| S6_SBR_MC/H:2,5     | Steel braced frames with Khorjini connections mid-code/height: 2 and 5 storeys |
| C1_MRF_LC/H:2,5,8   | Reinforced concrete moment frames, low-code/height: 2, 5, and 8 storeys |
| C1_MRF_MC/H:2,5,8   | Reinforced concrete moment frames, mid-code/height: 2, 5, and 8 storeys |
| C1_MRF_HC/H:2,5,8   | Reinforced concrete moment frames, high-code/height: 2, 5, and 8 storeys |
| C2_INFF_LC/H:2,5,8  | Reinforced concrete infilled frame, low-code/height: 2, 5, and 8 storeys |
| C2_INFF_MC/H:2,5,8  | Reinforced concrete infilled frame, mid-code/height: 2, 5, and 8 storeys |
| C2_INFF_HC/H:2,5,8  | Reinforced concrete infilled frame, high-code/height: 2, 5, and 8 storeys |
| C3_CSW_LC/H:5,8     | Reinforced concrete frames with the concrete shear wall, low-code/height: 5, 8 storeys |
| C3_CSW_MC/H:5,8     | Reinforced concrete frames with the concrete shear wall, mid-code/height: 5, 8 storeys |
| C3_CSW_HC/H:5,8     | Reinforced concrete frames with the concrete shear wall, high-code/height: 5, 8 storeys |
| C4_TUF_LC/H:2,5,8   | Reinforced concrete tunnel-form, low-code/height: 2, 5, and 8 storeys |
| C4_TUF_MC/H:2,5,8   | Reinforced concrete tunnel-form, mid-code/height: 2, 5, and 8 storeys |
| C4_TUF_HC/H:2,5,8   | Reinforced concrete tunnel-form, high-code/height: 2, 5, and 8 storeys |
| CM_LC/H:2           | Confined masonry buildings, low-code/height: 2 storeys |
| CM_MC/H:2           | Confined masonry buildings, mid-code/height: 2 storeys |
| CM_HC/H:2           | Confined masonry buildings, high-code/height: 2 storeys |
| UM/H:2              | Unreinforced masonry buildings/Height: 2 storeys |
| WD/H:2              | Wooden buildings/height: 2 storeys |
| ADOBE/H:2           | Adobe buildings/height: 2 storeys |

5 Results

5.1 Results of the capacity curves
Table 6  Generic two-linear capacity curves for steel and wooden Model Building Types (MBT)

| Building class | IMT       | $S_{dy}$ | $S_{du}$ | $S_{ay}$ | $S_{au}$ |
|----------------|-----------|----------|----------|----------|----------|
| S1_MRF_LC/H:2  | Sa (0.6 s) | 0.0261   | 0.128    | 0.6377   | 0.6377   |
| S1_MRF_LC/H:5  | Sa (0.6 s) | 0.0652   | 0.32     | 0.368    | 0.368    |
| S1_MRF_LC/H:8  | Sa (1.0 s) | 0.1043   | 0.512    | 0.2776   | 0.2776   |
| S1_MRF_MC/H:2  | Sa (0.6 s) | 0.0308   | 0.1754   | 0.7536   | 0.7536   |
| S1_MRF_MC/H:5  | Sa (0.6 s) | 0.077    | 0.4385   | 0.4349   | 0.4349   |
| S1_MRF_MC/H:8  | Sa (1.0 s) | 0.1233   | 0.7016   | 0.328    | 0.328    |
| S1_MRF_HC/H:2  | Sa (0.6 s) | 0.0356   | 0.2228   | 0.8696   | 0.8696   |
| S1_MRF_HC/H:5  | Sa (0.6 s) | 0.0889   | 0.557    | 0.5018   | 0.5018   |
| S1_MRF_HC/H:8  | Sa (1.0 s) | 0.1422   | 0.8913   | 0.3785   | 0.3785   |
| S3_MRF&CSW_LC/H:5 | Sa (0.6 s) | 0.0296   | 0.1304   | 0.6507   | 0.6507   |
| S3_MRF&CSW_LC/H:8 | Sa (0.6 s) | 0.0474   | 0.2086   | 0.5144   | 0.5144   |
| S3_MRF&CSW_MC/H:5 | Sa (0.6 s) | 0.0474   | 0.1541   | 1.0411   | 1.0411   |
| S3_MRF&CSW_MC/H:8 | Sa (0.6 s) | 0.0759   | 0.2465   | 0.823    | 0.823    |
| S3_MRF&CSW_HC/H:5 | Sa (0.6 s) | 0.0652   | 0.1778   | 1.4315   | 1.4315   |
| S3_MRF&CSW_HC/H:8 | Sa (0.6 s) | 0.1043   | 0.2844   | 1.1317   | 1.1317   |
| S4_SBR_LC/H:2  | Sa (0.3 s) | 0.0356   | 0.0948   | 1.389    | 1.389    |
| S4_SBR_LC/H:5  | Sa (0.6 s) | 0.0889   | 0.237    | 0.8016   | 0.8016   |
| S4_SBR_LC/H:8  | Sa (1.0 s) | 0.1422   | 0.3793   | 0.6046   | 0.6046   |
| S4_SBR_MC/H:2  | Sa (0.3 s) | 0.0375   | 0.1233   | 1.4631   | 1.4631   |
| S4_SBR_MC/H:5  | Sa (0.6 s) | 0.0936   | 0.3081   | 0.8443   | 0.8443   |
| S4_SBR_MC/H:8  | Sa (1.0 s) | 0.1498   | 0.493    | 0.6369   | 0.6369   |
| S4_SBR_HC/H:2  | Sa (0.3 s) | 0.0393   | 0.1517   | 1.5372   | 1.5372   |
| S4_SBR_HC/H:5  | Sa (0.6 s) | 0.0984   | 0.3793   | 0.8871   | 0.8871   |
| S4_SBR_HC/H:8  | Sa (1.0 s) | 0.1574   | 0.6068   | 0.6691   | 0.6691   |
| S5_DUAL_LC/H:2 | Sa (0.3 s) | 0.0417   | 0.0853   | 1.7243   | 1.7243   |
| S5_DUAL_LC/H:5 | Sa (0.6 s) | 0.1043   | 0.2133   | 0.995    | 0.995    |
| S5_DUAL_LC/H:8 | Sa (1.0 s) | 0.1669   | 0.3413   | 0.7505   | 0.7505   |
| S5_DUAL_MC/H:2 | Sa (0.3 s) | 0.0441   | 0.1043   | 1.8222   | 1.8222   |
| S5_DUAL_MC/H:5 | Sa (0.6 s) | 0.1102   | 0.2607   | 1.0516   | 1.0516   |
| S5_DUAL_MC/H:8 | Sa (1.0 s) | 0.1764   | 0.4172   | 0.7932   | 0.7932   |
| S5_DUAL_HC/H:2 | Sa (0.3 s) | 0.0465   | 0.1233   | 1.9202   | 1.9202   |
| S5_DUAL_HC/H:5 | Sa (0.6 s) | 0.1161   | 0.3081   | 1.1081   | 1.1081   |
| S5_DUAL_HC/H:8 | Sa (1.0 s) | 0.1858   | 0.493    | 0.8358   | 0.8358   |
| S6_SBR_LC/H:2  | Sa (0.3 s) | 0.0091   | 0.032    | 0.6193   | 0.6193   |
| S6_SBR_MC/H:2  | Sa (0.3 s) | 0.0229   | 0.08     | 0.3917   | 0.3917   |
| S6_SBR_MC/H:5  | Sa (0.6 s) | 0.0114   | 0.0389   | 0.7741   | 0.7741   |
| S6_SBR_MC/H:8  | Sa (0.6 s) | 0.0286   | 0.0971   | 0.4896   | 0.4896   |
| WD_H:2         | Sa (0.3 s) | 0.0057   | 0.0425   | 0.2796   | 0.2796   |
### Table 7 Fragility parameters for steel and wooden MBT

| Building class   | IM       | DS1         | DS2         | DS3         | DS4         |
|------------------|----------|-------------|-------------|-------------|-------------|
|                  |          | $\theta$    | $\beta$     | $\theta$    | $\beta$     | $\theta$    | $\beta$     | $\theta$    | $\beta$     |
| S1_MRF_HC/H:2    | Sa (0.6 s) | 0.6476      | 0.4284      | 0.526       | 0.4283      | 1.0502      | 0.4283      | 1.3771      | 0.4283      |
| S1_MRF_MC/H:2    | Sa (0.6 s) | 0.7884      | 0.4202      | 0.2397      | 0.4202      | 0.7168      | 0.4202      | 1.017       | 0.4202      |
| S1_MRF_HC/H:2    | Sa (0.6 s) | 0.9625      | 0.4181      | 0.0736      | 0.4181      | 0.365       | 0.4181      | 0.6451      | 0.4181      |
| S1_MRF_HC/H:5    | Sa (0.6 s) | 0.4139      | 0.5119      | 0.6604      | 0.512       | 1.1401      | 0.5119      | 1.4392      | 0.5119      |
| S1_MRF_MC/H:5    | Sa (0.6 s) | 0.5534      | 0.5027      | 0.4494      | 0.5027      | 0.9147      | 0.5027      | 1.2074      | 0.5027      |
| S1_MRF_HC/H:5    | Sa (0.6 s) | 0.7085      | 0.5072      | 0.1793      | 0.5072      | 0.6172      | 0.5072      | 0.8967      | 0.5072      |
| S1_MRF_HC/H:8    | Sa (1.0 s) | 0.7811      | 0.4596      | 0.3313      | 0.4596      | 0.8279      | 0.4596      | 1.1375      | 0.4596      |
| S1_MRF_MC/H:8    | Sa (1.0 s) | 0.9093      | 0.4677      | 0.127       | 0.4676      | 0.608       | 0.4676      | 0.9107      | 0.4677      |
| S1_MRF_HC/H:8    | Sa (1.0 s) | 1.065       | 0.4728      | 0.1484      | 0.4728      | 0.3036      | 0.4728      | 0.5922      | 0.4729      |
| S3_MRF&CSW_HC/H:5| Sa (0.6 s) | 0.9074      | 0.4015      | 0.0834      | 0.4015      | 0.3417      | 0.4016      | 0.6164      | 0.4016      |
| S3_MRF&CSW_HC/H:5| Sa (0.6 s) | 0.4205      | 0.4022      | 0.3038      | 0.4023      | 0.7285      | 0.4022      | 1.014       | 0.4023      |
| S3_MRF&CSW_HC/H:5| Sa (0.6 s) | 0.0325      | 0.4115      | 0.6177      | 0.4115      | 1.0288      | 0.4116      | 1.3124      | 0.4115      |
| S3_MRF&CSW_HC/H:5| Sa (0.6 s) | 0.804       | 0.4223      | 0.0315      | 0.4224      | 0.4628      | 0.4223      | 0.7415      | 0.4223      |
| S3_MRF&CSW_HC/H:5| Sa (0.6 s) | 0.3598      | 0.3959      | 0.3065      | 0.3958      | 0.6973      | 0.3959      | 0.96       | 0.3958      |
| S3_MRF&CSW_HC/H:8| Sa (0.6 s) | 0.0303      | 0.3822      | 0.5622      | 0.3822      | 0.9369      | 0.3822      | 1.1953      | 0.3823      |
| S4_SBR_HC/H:2    | Sa (0.3 s) | 0.2654      | 0.4433      | 0.8776      | 0.4433      | 1.2687      | 0.4433      | 1.5395      | 0.2654      |
| S4_SBR_HC/H:2    | Sa (0.3 s) | 0.3278      | 0.4441      | 1.0968      | 0.4441      | 1.5455      | 0.4441      | 1.8466      | 0.4433      |
| S4_SBR_HC/H:5    | Sa (0.3 s) | 0.3762      | 0.4237      | 1.2422      | 0.4237      | 1.7144      | 0.4237      | 2.0245      | 0.4237      |
| S4_SBR_HC/H:5    | Sa (0.6 s) | 0.2863      | 0.4305      | 0.2587      | 0.4305      | 0.6067      | 0.4305      | 0.8476      | 0.4305      |
| S4_SBR_HC/H:5    | Sa (0.6 s) | 0.2287      | 0.4253      | 0.4484      | 0.4253      | 0.8434      | 0.4253      | 1.1084      | 0.4253      |
| S4_SBR_HC/H:5    | Sa (0.6 s) | 0.1804      | 0.4275      | 0.6092      | 0.4274      | 1.0399      | 0.4274      | 1.3229      | 0.4274      |
| S4_SBR_HC/H:5    | Sa (1.0 s) | 0.6772      | 0.3807      | 0.1305      | 0.3807      | 0.2185      | 0.3807      | 0.4601      | 0.3807      |
| S4_SBR_HC/H:8    | Sa (1.0 s) | 0.614       | 0.3837      | 0.0705      | 0.3837      | 0.4698      | 0.3836      | 0.7376      | 0.3836      |
| S4_SBR_HC/H:8    | Sa (1.0 s) | 0.5584      | 0.377       | 0.2303      | 0.377       | 0.6606      | 0.377       | 0.9432      | 0.377       |
| S5_DUAL_HC/H:2   | Sa (0.3 s) | 0.4872      | 0.4286      | 0.9546      | 0.4286      | 1.2891      | 0.4287      | 1.5316      | 0.4287      |
| S5_DUAL_HC/H:2   | Sa (0.3 s) | 0.5288      | 0.4201      | 1.0833      | 0.4201      | 1.4561      | 0.4201      | 1.7194      | 0.4201      |
| S5_DUAL_HC/H:2   | Sa (0.3 s) | 0.6044      | 0.4368      | 1.2479      | 0.4369      | 1.6596      | 0.4368      | 1.945       | 0.4368      |
In this section, the results have been presented only for MBTs. The assumed MBTs for Iranian buildings taxonomy are shown in Table 5. As discussed earlier, an SDOF system was generated for each building type, considering the associated structural and dynamic properties presented in Table 4. These structural and dynamic properties were used to derive a generic backbone curve for each building type. The resulted generic Two-Linear backbone curves for MBTs have been shown in Table 6.

5.2 Results of the fragility functions

This section presents the resulting fragility parameters for the steel and wooden MBTs listed in Table 7. The resulting fragility parameters for other MBT are provided in Appendix A. As described in Table 7, the resulted fragility parameters are presented with the logarithmic mean (θ) and standard deviation (β) values. The Intensity Measure Types (IMT) for the derivation of fragility functions were selected considering the fundamental period of each building type. These IMTs are presented in Table 7. Figure 8 shows the resulted fragility curves for some MBTs.

6 Comparison of the fragility curves with empirical data derived from past earthquakes in Iran

In order to clarify the validity of the proposed fragility curves, a comparison has been provided between the presented fragility functions and damages observed during the past earthquakes in the country first. To this aim, observed damage data from Iran’s past earthquakes, from 1970 to 2017, have been collected. The information related to Iran’s
major past earthquakes is described in Table 8 (Sadeghi et al. 2015; Fallah Tafti et al. 2020).

Due to the lack of detailed and sufficient information on Iran’s past earthquake damages for different building types, the comparison has been accomplished only for some building types. The comparison between the fragility functions proposed in this study with the observed damage from past earthquakes has been illustrated for some building types in Fig. 9. The damages data due to past earthquakes in Iran have been extracted

![Some example of generated fragility functions](image-url)
from past research (Sadeghi et al. 2015; Izanloo and Yahyaabadi 2018; Biglari and Formisano 2020; Biglari et al. 2021), provided fragility curves based on PGA. In this study, these damage data were converted into Sa (0.3 s) and Sa (0.6 s) by using the PGA to Sa ratio extracted from the ground motion records used in this study. As shown in Fig. 9, it can be claimed that the fragility curves proposed in this study have mainly a good and appropriate agreement with observed damage data derived from past earthquakes in Iran.

Also, Fig. 10 compares the fragility curves of this study for eight building classes with the existing fragility curves found in the literature. To this aim, firstly, the expert judgment-based fragility curves proposed by Fallah Tafti et al. (2020) for common buildings in entire Iran and analytical ones by Kohrangi et al. (2021) for Isfahan are discussed. Overall, proposed herein fragility curves for Low-Rise unreinforced masonry (Fig. 10a), High-Code High-Rise reinforced concrete infilled frame (Fig. 10b), High-Code Mid-Rise Steel moment frame (Fig. 10c), and High-Code Mid-Rise RC moment frames building classes (Fig. 10d) are fairly close to those of Fallah Tafti et al. (2020) and Kohrangi et al. (2021) for all damage states (nearly identical for the High-Code Mid-Rise RC moment frames, and High-Code Mid-Rise Steel moment frame cases shown in Fig. 10c, d). Secondly, the analytical fragility curves proposed by Villar-Vega et al. (2017) for the most representative building classes in the Andean region of South America are compared. The fragility curves provided by Villar-Vega et al. (2017) for the High-Code Mid-Rise RC moment frames building class (Fig. 10f) show an approximately equal fragility at all damage grades with those proposed in this study. The only

| Earthquake        | Province                | Date          |
|-------------------|-------------------------|---------------|
| Gharnaveh         | Golestan                | 30 July 1970  |
| Gharnaveh         | Golestan                | 10 April 1972 |
| Qir-Karzin        | Fars                    | 21 June 1990  |
| Manjil-Rudbar     | Gilan                   | 21 June 1990  |
| Manjil-Rudbar (Manjil) | Gilan              | 21 June 1990  |
| Manjil-Rudbar (Rudbar) | Gilan            | 21 June 1990  |
| Manjil-Rudbar (Rasht) | Gilan                | 21 June 1990  |
| Manjil-Rudbar (Loushan) | Gilan             | 21 June 1990  |
| Lordegan          | Chaharmahal and Bakhtiari| 4 March 1992  |
| Golestan          | Ardabil                 | 28 February 1997 |
| Qayen             | Khorasan                | 10 May 1997   |
| Bam               | Kerman                  | 26 December 2003 |
| Zarand            | Kerman                  | 22 February 2005 |
| Varzaghan         | Kerman                  | 11 August 2012 |
| EMME1             | Mashhad, Khorasan       | 2013          |
| EMME2             | Mashhad, Khorasan       | 2013          |
| Borazjan          | Bushehr                 | 28 Nov 2013   |
| Sarpol-e-Zahab (Kuick) | Kermanshah            | 12 Nov 2017   |
| Sarpol-e-Zahab City | Kermanshah            | 12 Nov 2017   |

*EMME* Earthquake model of Middle East
exception is for the complete damage state of the Low-Rise unreinforced masonry building class (Fig. 10e), which shows less fragility according to Villar-Vega et al. (2017) predictions. Meanwhile, the expert judgment-based fragility curves proposed by Fallah Tafti et al. (2020) for low-rise unreinforced masonry (Fig. 10a) are more realistic.
than the ones of Villar-Vega et al. (2017). Indeed, the IIEES Structural research center experts expected more damage to the Iranian unreinforced masonry building class than

Fig. 10 Comparison between analytical fragility curves proposed herein (green lines) and by Fallah Tafti et al. (2020) (red lines), Kohrangi et al. (2021) (purple lines), and Villar-Vega et al. (2017) (blue lines) for a, e Low-Rise unreinforced masonry, b High-Code High-Rise reinforced concrete infilled frame, c High-Code Mid-Rise Steel moment frame, d, f High-Code Mid-Rise RC moment frame building class
the fragility curves from Villar-Vega et al. (2017) for South America. So, this study is predicting more fragility at the complete damage state for Iran.

7 Summary and conclusion

Developing fragility functions is one of the most critical steps in seismic risk assessment. The lack of comprehensive and reliable fragility functions for common buildings in Iran is an essential gap to evaluate the extent of damage to buildings due to the potential earthquake hazard. For this reason, an extensive review was performed on previous studies in the country, and their beneficial data have been collected. The extracted data have been utilized to identify all common buildings in Iran and develop cogent fragility functions for them. This work has been done through the following steps:

(1) In the initial step, by conducting comprehensive studies, common buildings in Iran were identified and divided into 31 categories based on the type of materials, lateral resisting system, height, and code level.
(2) Then, considering structural and dynamic parameters, an equivalent single-degree-of-freedom oscillator with a generic backbone curve and a hysteresis behavior has been defined for buildings in each class.
(3) A large collection of ground motion records has been provided from the IIEES SGMR Toolbox.
(4) The non-linear time-history analyses were performed on SDOF systems defined for each building class utilizing a set of 300 ground motion records.
(5) Finally, approximately 300 fragility functions were developed for Iranian building taxonomy using the cloud analysis methodology proposed by Jalayer et al. (2015).
(6) The developed fragility functions have been compared with experimental data from past earthquakes in Iran and with similar fragility curves found in the literature. The results showed that generated fragility functions follow the empirical data reasonably well and show good agreement with the fragility curves produced in the literature.

As discussed earlier, the fragility functions developed in this study have been mainly in good agreement with empirical data from past earthquakes. So, the proposed fragility functions can be used directly to assess the damage to human and economic losses due to earthquake scenarios, probabilistic risk analysis, and risk management. Lastly, although the obtained results are encouraging, the awareness of the limitations of the current study is significant. These fragility functions have been developed based on a simplified numerical method and expert judgment. So, it is recommended for future studies to focus on:

- Refining numerical models by using more detailed characteristics of the buildings, proper identification of the structural parameters of the buildings, and considering structural deficiencies.
- Defining more accurate backbone curves for Iranian common building types based on these numerical models.
- A comprehensive study on some existing building types in the country, which sufficient information has not existed (such as precast concrete buildings).
- Providing instructions for collecting building damage data for future events.
These steps allow for a more precise evaluation of the earthquake’s impact on Iranian buildings stock, thus obtaining more reliable risk analyses.

**Appendix A The resulting fragility parameters for concrete, masonry, adobe, and other steel MBTs**

| Taxonomy       | IM     | DS1   | DS2   | DS3   | DS4   |
|----------------|--------|-------|-------|-------|-------|
|                |        | $\theta$ | $\beta$ | $\theta$ | $\beta$ | $\theta$ | $\beta$ | $\theta$ | $\beta$ |
| S2_INFF_LC/H:2 | Sa (0.3 s) | 0.1177 | 0.5186 | 0.8548 | 0.5187 | 1.2528 | 0.5186 | 1.5135 | 0.5187 |
| S2_INFF_MC/H:2 | Sa (0.3 s) | 0.3326 | 0.517 | 1.1678 | 0.5169 | 1.6082 | 0.517 | 1.8945 | 0.517 |
| S2_INFF_HC/H:2 | Sa (0.3 s) | 0.6152 | 0.5071 | 1.4958 | 0.507 | 1.9688 | 0.5071 | 2.2781 | 0.5071 |
| S2_INFF_LC/H:5 | Sa (0.6 s) | −0.5274 | 0.4631 | 0.1231 | 0.4631 | 0.4744 | 0.4631 | 0.7043 | 0.4631 |
| S2_INFF_MC/H:5 | Sa (0.6 s) | −0.3986 | 0.475 | 0.2999 | 0.4751 | 0.6681 | 0.475 | 0.9076 | 0.475 |
| S2_INFF_HC/H:5 | Sa (0.6 s) | −0.2179 | 0.4845 | 0.4877 | 0.4845 | 0.8668 | 0.4845 | 1.1147 | 0.4844 |
| S2_INFF_LC/H:8 | Sa (0.6 s) | −0.4574 | 0.419 | 0.222 | 0.419 | 0.589 | 0.419 | 0.8294 | 0.419 |
| S2_INFF_MC/H:8 | Sa (0.6 s) | −0.3463 | 0.4139 | 0.3766 | 0.4139 | 0.7574 | 0.4139 | 1.005 | 0.4139 |
| S2_INFF_HC/H:8 | Sa (0.6 s) | −0.1835 | 0.411 | 0.5322 | 0.4111 | 0.9165 | 0.4111 | 1.1678 | 0.4111 |
| C1_MRF_LC/H:2 | Sa (0.6 s) | −0.7505 | 0.4014 | −0.4159 | 0.4014 | −0.1783 | 0.4014 | −0.0068 | 0.4014 |
| C1_MRF_MC/H:2 | Sa (0.6 s) | −0.6786 | 0.4082 | −0.1243 | 0.4082 | 0.199 | 0.4083 | 0.4158 | 0.4082 |
| C1_MRF_HC/H:2 | Sa (0.6 s) | −0.6421 | 0.4044 | 0.0923 | 0.4044 | 0.4683 | 0.4044 | 0.7109 | 0.4044 |
| C1_MRF_LC/H:5 | Sa (1.0 s) | −1.136 | 0.4383 | −0.7457 | 0.4382 | −0.4684 | 0.4382 | −0.2682 | 0.4382 |
| C1_MRF_MC/H:5 | Sa (1.0 s) | −1.0887 | 0.479 | −0.4476 | 0.4791 | −0.0734 | 0.479 | 0.1776 | 0.4791 |
| C1_MRF_HC/H:5 | Sa (1.0 s) | −1.0607 | 0.4866 | −0.2265 | 0.4866 | 0.2004 | 0.4866 | 0.4758 | 0.4865 |
| C1_MRF_LC/H:8 | Sa (1.0 s) | −0.8967 | 0.5402 | −0.4888 | 0.5402 | −0.199 | 0.5402 | 0.0104 | 0.5402 |
| C1_MRF_MC/H:8 | Sa (1.0 s) | −0.8534 | 0.5568 | −0.1962 | 0.5567 | 0.1873 | 0.5568 | 0.4446 | 0.5568 |
| C1_MRF_HC/H:8 | Sa (1.0 s) | −0.8287 | 0.5616 | 0.0271 | 0.5615 | 0.4652 | 0.5615 | 0.7477 | 0.5616 |
| C2_INFF_LC/H:2 | Sa (0.3 s) | −0.5651 | 0.4328 | 0.185 | 0.4329 | 0.546 | 0.4329 | 0.775 | 0.4329 |
| C2_INFF_MC/H:2 | Sa (0.3 s) | −0.1374 | 0.4333 | 0.5668 | 0.4333 | 0.9247 | 0.4333 | 1.1549 | 0.4334 |
| Taxonomy         | IM     | DS1  | DS2  | DS3  | DS4  |
|------------------|--------|------|------|------|------|
|                  | \(\theta\) | \(\beta\) | \(\theta\) | \(\beta\) | \(\theta\) | \(\beta\) |
| C2_INFF_HC/H:2   | Sa (0.3 s) | 0.3489 | 0.4613 | 1.0678 | 0.4613 | 1.4454 | 0.4613 | 1.6907 | 0.4613 |
| C2_INFF_LC/H:5   | Sa (1.0 s) | -1.7172 | 0.4094 | -0.859 | 0.4094 | -0.4456 | 0.4094 | -0.1831 | 0.4094 |
| C2_INFF_MC/H:5   | Sa (1.0 s) | -1.2431 | 0.4083 | -0.5582 | 0.4083 | -0.2103 | 0.4082 | 0.0135 | 0.4082 |
| C2_INFF_HC/H:5   | Sa (1.0 s) | -0.8658 | 0.405 | -0.2341 | 0.4049 | 0.0976 | 0.4049 | 0.313 | 0.4049 |
| C2_INFF_LC/H:8   | Sa (1.0 s) | -1.6485 | 0.4916 | -0.7116 | 0.4916 | -0.2604 | 0.4916 | 0.026 | 0.4916 |
| C2_INFF_MC/H:8   | Sa (1.0 s) | -1.27 | 0.4674 | -0.4544 | 0.4674 | -0.0401 | 0.4674 | 0.2264 | 0.4674 |
| C2_INFF_HC/H:8   | Sa (1.0 s) | -0.9337 | 0.4299 | -0.1846 | 0.4298 | 0.2088 | 0.4298 | 0.4643 | 0.4298 |
| C3_CSW_HC/H:5    | Sa (0.6 s) | -0.5701 | 0.4058 | 0.0793 | 0.4059 | 0.4221 | 0.4058 | 0.6451 | 0.4058 |
| C3_CSW_MC/H:5    | Sa (0.6 s) | -0.4152 | 0.4241 | 0.2846 | 0.4241 | 0.6445 | 0.4241 | 0.8769 | 0.424 |
| C3_CSW_HC/H:5    | Sa (0.6 s) | -0.2574 | 0.4382 | 0.4846 | 0.4382 | 0.8582 | 0.4382 | 1.0982 | 0.4382 |
| C3_CSW_LC/H:8    | Sa (0.6 s) | -0.674 | 0.4379 | 0.0574 | 0.4379 | 0.4436 | 0.4379 | 0.6949 | 0.4379 |
| C3_CSW_MC/H:8    | Sa (0.6 s) | -0.5299 | 0.4275 | 0.2396 | 0.4274 | 0.6353 | 0.4275 | 0.8907 | 0.4274 |
| C3_CSW_HC/H:8    | Sa (0.6 s) | -0.3999 | 0.419 | 0.4013 | 0.419 | 0.805 | 0.419 | 1.0642 | 0.419 |
| C4_TUF_LC/H:2    | Sa (0.3 s) | 0.0256 | 0.4441 | 0.4546 | 0.4441 | 0.7282 | 0.444 | 0.9177 | 0.4441 |
| C4_TUF_MC/H:2    | Sa (0.3 s) | 0.2175 | 0.4575 | 0.6942 | 0.4576 | 0.9895 | 0.4575 | 1.1919 | 0.4576 |
| C4_TUF_HC/H:2    | Sa (0.3 s) | 0.3957 | 0.482 | 0.9231 | 0.482 | 1.2432 | 0.4819 | 1.4608 | 0.4819 |
| C4_TUF_LC/H:5    | Sa (0.6 s) | -0.5351 | 0.3939 | -0.0999 | 0.394 | 0.1779 | 0.394 | 0.3703 | 0.394 |
| C4_TUF_MC/H:5    | Sa (0.6 s) | -0.3731 | 0.4067 | 0.113 | 0.4067 | 0.4141 | 0.4067 | 0.6204 | 0.4067 |
| C4_TUF_HC/H:5    | Sa (0.6 s) | -0.2269 | 0.4217 | 0.2934 | 0.4217 | 0.6092 | 0.4217 | 0.8239 | 0.4217 |
| C4_TUF_HC/H:5    | Sa (0.6 s) | -0.4808 | 0.4293 | 0.0073 | 0.4293 | 0.319 | 0.4293 | 0.5349 | 0.4293 |
| C4_TUF_MC/H:8    | Sa (0.6 s) | -0.3126 | 0.419 | 0.2209 | 0.419 | 0.5514 | 0.4189 | 0.7779 | 0.419 |
| C4_TUF_HC/H:8    | Sa (0.6 s) | -0.1799 | 0.4212 | 0.3884 | 0.4213 | 0.7333 | 0.4213 | 0.9677 | 0.4213 |
| CM_LC/H:2        | Sa (0.3 s) | -0.6889 | 0.3989 | -0.2111 | 0.3989 | 0.0658 | 0.3988 | 0.2511 | 0.3989 |
| CM_MC/H:2        | Sa (0.3 s) | -0.5499 | 0.4094 | -0.0756 | 0.4093 | 0.2014 | 0.4093 | 0.3874 | 0.4093 |
| CM_HC/H:2        | Sa (0.3 s) | -0.4098 | 0.416 | 0.069 | 0.416 | 0.3487 | 0.416 | 0.5364 | 0.416 |
| UM_H2            | Sa (0.3 s) | -1.214 | 0.3997 | -0.6068 | 0.3997 | -0.2807 | 0.3997 | -0.0675 | 0.3998 |
| ADOBE_H2         | Sa (0.3 s) | -1.5719 | 0.4448 | -0.8758 | 0.4448 | -0.5142 | 0.4448 | -0.28 | 0.4448 |
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Conflict of interest  The authors declare that they have no conflict of interest.

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