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Fragility analysis of bridge structures: a global perspective & critical review of past & present trends

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Abstract

Bridges are vital to modern transportation infrastructure, providing convenient and efficient access to different locations. However, these structures are susceptible to forces that can cause significant damage and pose a hazard in the event of seismic activity. A country's economy relies heavily on its bridge infrastructure, but many older bridges built before 1970 are showing signs of deterioration due to climate change and other factors. At the time of their construction, seismic design codes did not provide sufficient guidance on proper design and detailing to ensure ductility and capacity, resulting in deficient bridges. This paper provides a brief overview of the literature on the seismic behaviour of bridges and the analytical methods used to evaluate their performance. Various factors that influence the behaviour of different types of bridges are also discussed. This paper aims to establish a theoretical foundation for selecting appropriate methods to analyze bridge structures, prioritizing retrofitting, pre-earthquake planning, and loss measurement tools. The seismic design philosophies and analytical methods are elaborated in-depth, including the methodology to develop fragility curves. The paper also discusses the fragility analysis of retrofitted bridges.

Keywords: Fragility analysis, Bridges, Non-linear static pushover analysis, Dynamic time history analysis, Incremental dynamic analysis, Failure probability

1 Introduction

The primary goal of designing earthquake-safe bridges is to ensure that communication channels remain functional at an acceptable level during seismic activity. To achieve this objective, the design concept focuses on maintaining an appropriate level of damage probability for three different earthquake intensity levels throughout the lifespan of the structure.

The first level pertains to earthquakes that have a return period of less than 50% of the bridge's lifespan, which may occur multiple times over the structure's life. In this scenario, any damage should be minor, and communication channels must not be disrupted. While the bridge may sustain significant damage, it should not collapse.

The second level is defined for earthquakes that have a return period of 50% to 150% of the bridge's lifespan. In this case, the bridge should be restored continually to meet standards for both vehicles and earthquake loading. It should also be used for emergency traffic with easy and rapid repairs. The degree to which the bridge is restored is determined by the supervisory authority.

The third level applies to earthquakes that have a return period of more than 150% of the bridge's lifespan. In this situation, the bridge may sustain significant damage, but it should not collapse. While damages could be severe, the bridge should be serviceable after temporary repairs for traffic incidents and functional after permanent repairs for lower vehicle loads.

1.1 Past damages in bridge structures

The consequences of bridge damage caused by earthquakes can be significant, even if the damage is not immediately obvious. Bridge collapse following an earthquake can hinder emergency response efforts, potentially putting lives at risk and requiring replacement of the bridge unless alternate routes are available. Suspension bridges are particularly crucial components of transportation systems, and their closure can have severe economic effects over time. The reasons for bridge damage and collapse can vary, with earthquakes and scouring being the most common causes for Reinforced Concrete (RC) bridges (Zaky et al. 2020; Huang et al. 2020). Each earthquake and geological condition is unique, and bridge design and construction practices vary by country. Improvements in seismic design practices have been made since the 1971 San Fernando earthquake in the western United States, and the exact causes and consequences of bridge damage can be difficult to determine and may require extensive investigation. Figure 1 portrays the damages caused to bridges by earthquakes in different countries from 2000 to the

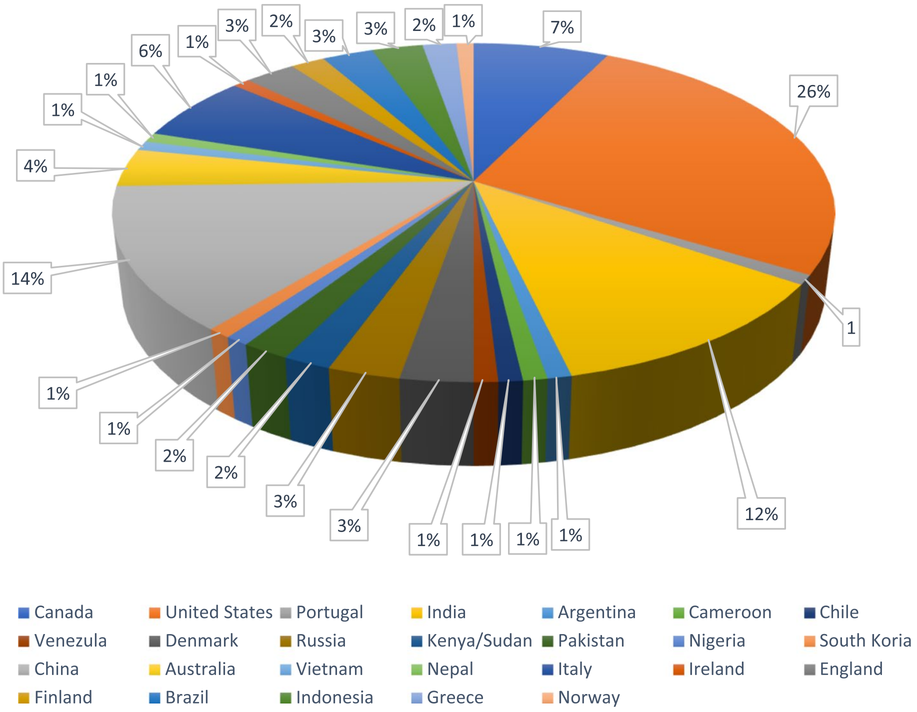


Fig. 1 Country-wise bridge damages due to earthquakes from the year 2000 to present

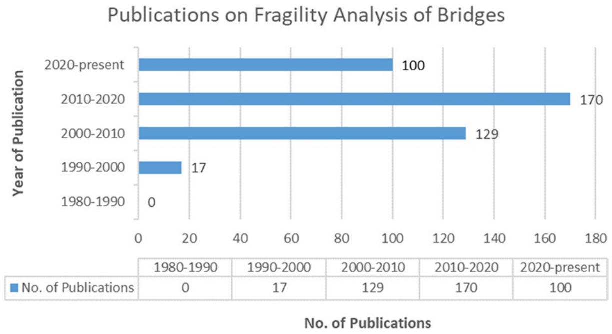
present day. The figure highlights that the United States, India, and China had the most substantial bridge damages resulting from earthquakes.

Despite the uncertainties and variations, it is possible to anticipate damages before frequent earthquakes occur. Thus, it is important to gain insights into the structural behaviour and identify potential issues in both current and future bridges, considering their vulnerabilities. The damages recorded in the past have driven improvements in earthquake engineering standards and practices. The classification of damages into two categories was attempted: those induced by earthquake ground shaking or deformation, which resulted in the collapse of the entire bridge structure, and secondary damages caused by the redistribution of internal forces triggered by earthquake ground shaking or deformation, leading to structural failures elsewhere in the bridge.

1.2 Fragility analysis

Fragility refers to the vulnerability or sensitivity of a structure, which makes it prone to break or damage easily. The term originates from the Latin word 'fragile,' meaning the ability to break down or deteriorate quickly. The fragility of a component or system is defined as its probability of failure, conditioned on a level of excitation (ground motion, spectral acceleration, spectral velocity, etc.) that is consistent with the specification of the hazard (Ellingwood and Song 1996). Fragility curves are now an established method for assessing earthquake risk in civil engineering structures such as buildings, bridges, and dams. These curves are used to prioritize retrofitting, pre-earthquake planning, and loss measurement tools. They indicate the extent to which a structure may be distressed by various earthquake intensities. This information is particularly useful for pre-earthquake planning in regions with moderate seismic activity. In light of the recorded damages caused by earthquakes to bridge structures, there is a growing need for condition assessments of bridges before future earthquakes occur. Figure 2 shows the year-wise publications on the fragility of bridge structures, which can be valuable resources for further research.

A study by Billah and Alam (2015) reviews seismic fragility assessment of highway bridges, covering topics such as analytical methods, empirical fragility functions, and



	1980-1990	1990-2000	2000-2010	2010-2020	2020-present
■ No. of Publications	0	17	129	170	100

Fig. 2 Year-wise publications on fragility analysis of bridges from referred literature (Muntasir Billah and Shahria Alam 2015)

probabilistic seismic hazard analysis (Ellingwood and Song 1996). Extensive coverage of analytical methods is a highlight, with detailed descriptions and advantages and limitations discussed. Authors review empirical fragility functions and factors affecting fragility. PSHA methodology and importance of considering uncertainties highlighted. Limitations include focus on highway bridges and exclusion of other hazards.

Zhang et al. (2020) presented a probabilistic seismic fragility analysis of highway bridges in Northern California (Zhao et al. 2021). The fragility functions were developed for different bridge types, and the effects of bridge parameters and seismic hazard levels were studied. The results showed that the probability of exceeding damage states increases with the intensity of ground motion and the age of the bridge. A study by Another study illustrates a fragility analysis of a steel girder bridge using both probabilistic and deterministic approaches (Cao et al. 2020). The study compared the results of fragility curves obtained from different analytical methods, such as nonlinear time history analysis and pushover analysis. The results showed that the probabilistic method was more accurate in predicting the fragility of the bridge.

A case study was conducted using a continuous beam bridge and different construction methods, incorporating the aging factor of materials during the operation period (Zhong et al. 2023a). This two-stage seismic risk analysis provides a comprehensive understanding of the bridge's seismic risk throughout its entire lifespan, including the impact of factors such as atmospheric environment, seismic intensity, multiple earthquakes, and construction methods. The study found that the construction stage accounts for 5% or more of the entire life-cycle seismic loss, which can be reduced significantly by selecting construction methods that minimize seismic risk during construction.

Studies examining the impact of vertical ground motion on peak displacement of friction isolation bearings have typically been deterministic, and probabilistic research in this area is lacking. Therefore, a statistical approach was adopted to investigate the probabilistic distribution of displacement errors caused by neglecting vertical ground motions (Zhong et al. 2023b). The resulting error follows a Gaussian distribution, and the relationship between the Gaussian function and the intensity of both horizontal and vertical ground motions is quantitatively examined. The findings indicate that the mean value of the error is close to zero, while the standard deviation increases significantly with ground motion intensity. This suggests that vertical ground motion has minimal impact on the mean seismic demand, but strongly affects the dispersion. To facilitate seismic design, various quantiles of the Gaussian functions were defined as increment coefficients. A set of empirical formulas was proposed to predict the value of the increment coefficient, providing a convenient method for designers to ensure the safety of bridge structures. The residual displacement of a column can greatly impact a bridge's functionality following an earthquake. The study involved constructing a nonlinear finite element model of a simply supported beam bridge, comparing the seismic performance of reinforced concrete, unbonded prestressed reinforced concrete (UBPRC), and fully prestressed columns was performed (Liu et al. 2023). Fragility analysis was performed using quasi-static residual displacement. The findings indicated that quasi-static residual displacement only affects the vulnerability of the bridge system in the collapse damage limit state. The UBPRC column was found to strike a good balance between vulnerability arising from peak displacement and residual displacement.

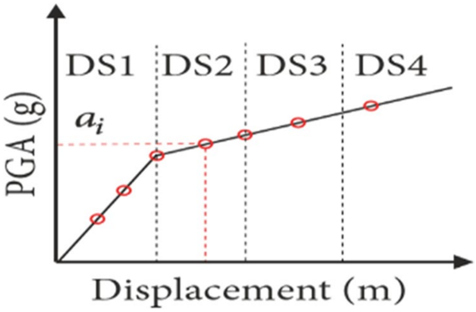


Fig. 3 Representation of damage states for bridges (Guo et al. 2019)

1.2.1 Fragility analysis outputs (fragility curves)

The fragility curves classify structural damages into three categories: (i) damage to structural systems, (ii) damage to non-structural elements sensitive to drift, and (iii) damage to non-structural elements sensitive to acceleration. The curves also divide damages into four physical states: slight, moderate, extensive, and complete, based on the degree of bridge response. Physical damage states are crucial in measuring the loss of structural stability in bridges caused by earthquakes, making them a valuable tool for assessing losses. The complete state of structural damage is primarily responsible for the death rate, with partial or total bridge collapse dominating this type of damage and directly impacting economic losses, such as repair and replacement costs.

1.2.2 Damage states of bridges

In fragility assessment, one crucial step is to estimate the degree of seismic damage, either quantitatively or qualitatively. Damage states (DSs) are discrete and associated with the structural capacity of a system or its part, labeled with various limit values of a damage index (Zhang and Huo 2009). To establish damage states for bridges and their components, a suitable method is to assign a functional level to each condition. Seismic vulnerability assessments of engineered structures widely use slight, moderate, significant, and complete damage as four levels of damage (NIBS 2015). Figure 3 illustrates various damage levels in bridge structures (Guo et al. 2019). Different demand parameters are used to measure the DS of bridge components.

Table 1 summarizes the Damage Index (DI) criteria for various Damage States (DSs). Different researchers have adopted the Limit States values of curvature ductility $\mu\kappa$ shown in Fig. 4 (Choi et al. 2004). In addition to potential damage in columns, substantial displacement in isolation devices and adjacent structural elements occurs when a bridge is base-isolated. DSs for isolation devices are established through experimentation and evaluation of pounding and unseating. Bearing displacement or shear strain are often used to describe DSs, as indicated in Table 1. The cyclic loading factor β, cumulative energy ductility μ_h, and displacement and ultimate ductility of the bridge piers μ_d and μ_u, respectively, are represented by the equation (Karim and Yamazaki 2001).

Table 1 Damage state limits for bridge piers and bearing systems (Choi et al. 2004; Karim and Yamazaki 2001; Hwang et al. 2001; Parghi and Alam 2017; Basnet and Suwal 2019)

Bridge Components		Damage Index	Slight (DS = 1)	Moderate (DS = 2)	Extensive (DS = 3)	Collapse (DS = 4)
Columns	A	Physical phenomenon	Cracking and spalling	Moderate cracking and spalling	Degradation without collapse failure	Failure leading to collapse
	B	Element ductility μκ	$2>\mu_\kappa>1$	$4>\mu_\kappa>2$	$7>\mu_\kappa>4$	$\mu_\kappa>7$ (Choi et al. 2004)
	C	Displacement ductility μd cracking	$\mu_d>\mu$ first-yield (1.0)	$\mu_d>\mu$ first-yield (1.20)	$\mu_d>\mu$ first-yield (1.76)	$\mu_d>\mu$ first-yield (4.76) (Hwang et al. 2001)
	D	$\gamma=(\mu_d+\beta_{\mu h})/\mu_u$	$0.40>\gamma>0.14$	$0.60>\gamma>0.40$	$1.0>\gamma>0.60$	$\gamma>1.0$ (Karim and Yamazaki 2001)
	E	Load carrying capacity loss βh, βv	$\beta_h>0\%$ $\beta_v>5\%$	$\beta_h>2\%$ $\beta_v>10\%$	$\beta_h>5\%$ $\beta_v>25\%$	$\beta_h>20\%$ $\beta_v>50\%$ (Basnet and Suwal 2019)
Bearing Systems	F	Drift ratio θ	$\theta>0.007$ 0.2%–0.5%	$\theta>0.015$ 0.5%–1.5%	$\theta>0.025$ 1.5%–2.5%	$\theta>0.050$ >2.5% (Parghi and Alam 2017)
	G	Displacement δ	$\delta>0$ mm	$\delta>50$ mm	$\delta>10\,0$ mm	$\delta>150$ mm (Choi et al. 2004)

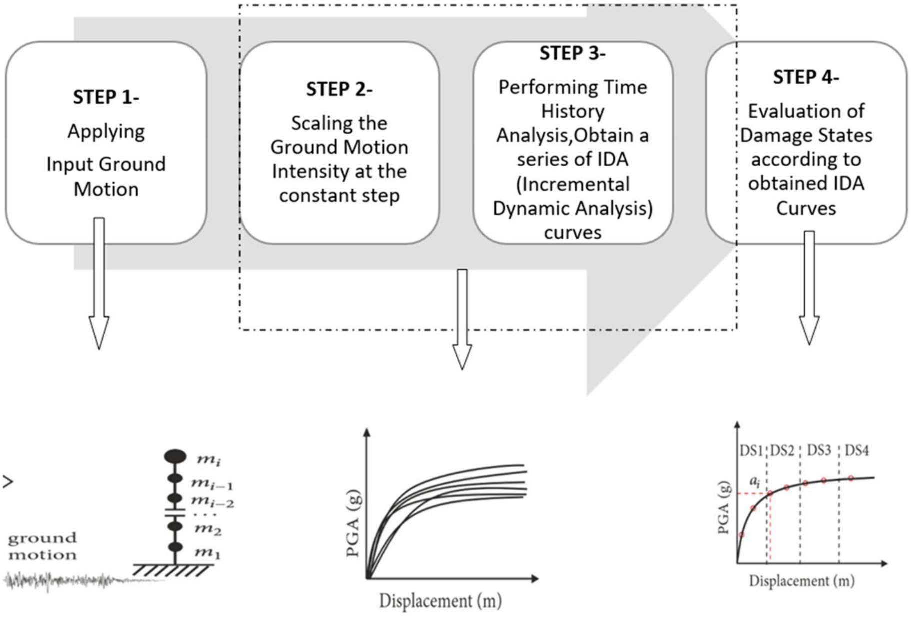


Fig. 4 Procedure of incremental dynamic analysis (Guo et al. 2019)

1.3 Seismic analysis methods for bridge structures

Seismic analysis techniques are employed to assess a structure's response under earthquake loading, making it a crucial aspect of structure design in earthquake-prone areas. A well-designed structure should sway back and forth during ground shaking or severe wind storms, referred to as its fundamental mode. However, a structure's higher response modes could be activated during an earthquake due to the combined effect of multiple loads, such as earthquake and wind loads acting simultaneously. These analyses can be either linear or nonlinear, with the latter involving significant efforts to achieve significant objectives. Nonlinear analysis is necessary to evaluate a structure's performance in the following cases: designing or analyzing retrofit measures for pre-existing structures such as bridges, buildings, and dams, designing new structures that exhibit satisfactory responses during hazardous events, and assessing a structure's performance and stability as required. Inelastic, nonlinear analytical techniques are still in the developing phase, in contrast to well-established linear design and analysis methods. Therefore, innovative skills and techniques are needed to implement performance-based design methodologies. The plastic analysis principle considers the plastic behaviour of a structure, but its limitation lies in conditions based on deformation and strength.

Fragility analysis is used to assess the vulnerability of structures to potential hazards and risks. Here are some common fragility analysis methods that are used specifically for structures:

- ATC-40: This method was developed by the Applied Technology Council (ATC) and is used to assess the seismic vulnerability of buildings.
- ASCE 41: This method was developed by the American Society of Civil Engineers (ASCE) and is used to assess the seismic performance of existing buildings.
- FEMA P-58: This method was developed by the Federal Emergency Management Agency (FEMA) and is used to assess the seismic performance of buildings and other structures.
- FEMA 356: This method was also developed by FEMA and is used to assess the seismic performance of buildings.
- ASCE 7–16: This method is used to determine the design loads for buildings and other structures, including wind, seismic, and snow loads.
- AISC 360: This method is used to design steel structures and includes provisions for structural stability, strength, and ductility.
- ACI 318: This method is used to design concrete structures and includes provisions for structural stability, strength, and durability.
- Eurocode 8: This is a set of European standards that provides guidelines for the seismic design of structures.

These are just a few of the many fragility analysis methods that are used specifically for structures. Depending on the type of structure and the hazard being evaluated, different methods may be used or combined to provide a comprehensive assessment of the structure's vulnerability. However, the seismic methods can be divided into two major categories as described in the following sections.

1.3.1 Static methods

Non-linear static pushover method: Pushover analysis is a type of structural analysis that involves applying gravity and lateral loads to a structure while controlling the displacement pattern. The lateral load represents the amount of shear at the base of the structure caused by an earthquake. The output of a pushover analysis is typically presented as a pushover curve, which shows the relationship between a strength parameter and a specific deflection value. This can help to assess the performance of a structure and the strength of its critical members in relation to displacement. The results of pushover analysis can also provide valuable information on the ductile behaviour of the structural system, load rate, and deviation at fault.

The process for conducting a pushover analysis is illustrated in Fig. 5. Firstly, the seismic load distribution is determined based on the first mode of vibration, as shown in Fig. 5. The next step involves plotting the shear force diagram, which is dependent on displacement, to form a force–displacement curve. This force–displacement curve is then transformed into a bi-linear curve using the demand and capacity curves. Figure 5 provides an explanation of the capacity curve or force–displacement curve. Finally, the target displacement is calculated based on these curves, as represented in Fig. 5. Then, based on the evaluated seismic response of an element, DSs are assigned, as depicted in Fig. 3.

Extensive research has been conducted on fragility analysis in conjunction with non-linear pushover analysis. Parghi and Alam (2017) have developed fragility curves for a non-seismically built typical single circular (RC) bridge pier (Parghi and Alam 2017). They evaluated various characteristics, including concrete strength, yield strength of longitudinal steel rebar, their number, axial load level, reinforced and carbon fibre, and the quantitative relationship between shear span and depth on the fragility analysis of bridges. Dynamic analysis and progressive non-linear static pushover analysis (NSPA) were performed to investigate the dynamic and non-linear behaviour of retrofitted

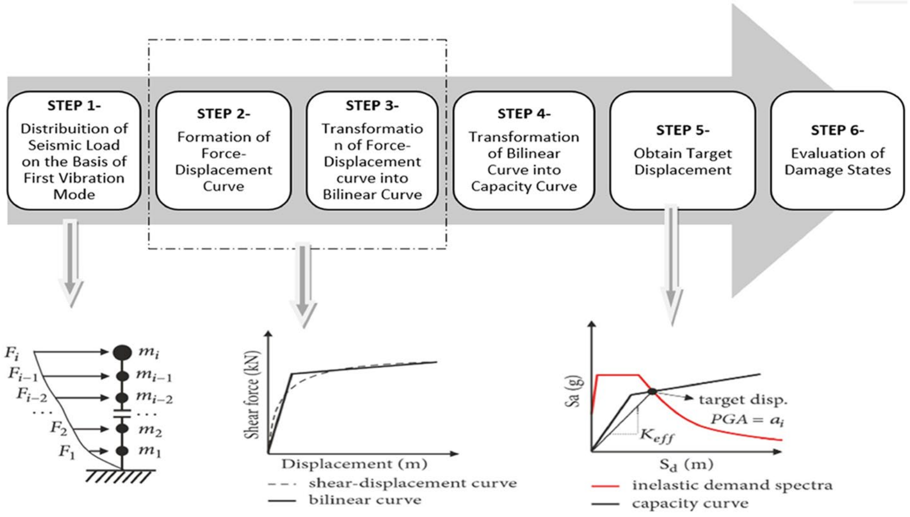


Fig. 5 Procedure of pushover analysis (Guo et al. 2019)

bridge piers, using a suitable set of seismic ground motions with a specific range of PGA. The fragility curves for non-seismically built RC circular bridge piers were generated using collapse drift as a demand parameter. The influence of various factors on the fragility curves of the pier was interpreted randomly. Parghi and Alam (2017) discovered that reinforcement, axial load level, and span-depth ratio have a significant impact on the collapse fragility of retrofitted bridge piers.

Furthermore, Guo et al. (2019) conducted a study to assess the applicability of non-linear pushover analysis (NLPA) in analyzing the fragility of railway bridges. They investigated the effect of different pier heights on the seismic fragility of the piers using the same analytical approach (Guo et al. 2019). The study found that the response of piers to earthquakes from pushover only complies with those from incremental dynamic analysis (IDA) for peak ground accelerations less than 0.4 g. Additionally, the study concluded that taller piers are more seismically efficient than shorter piers.

In a separate research work, Basnet and Suwal (2019) used pushover analysis to assess the seismic vulnerability of reinforced concrete bridge piers. They established fragility curves for the multi-bent pier of a 3-span continuous bridge with varying skew angles (Basnet and Suwal 2019). The study revealed that the transverse vibration period of a skew bridge increases as the skew angle of the bridge increases. Moreover, the probability of failure of a skew bridge increases with the variation in skew angle from 0 to 60 degrees due to the decrease in the stiffness of the lateral load resisting element and the combined axial, flexural, and torsional effects introduced by the skew angle variation.

Elmy and Nakamura conducted an experimental study on hybrid steel-reinforced concrete (SRC) bridges using the same analytical procedure. The study found that the new SRC form of bridges (steel rolled H-section SRC bridge) has adequate ductility and bending strength. In addition, the imposed load was efficiently transferred from the girder to the pier via stiff connection, and the cracks on the concrete surfaces were within permissible limits (Elmy and Nakamura 2017).

However, the drift capacity of I-girder and box girder bridges was found to be low (Patil et al. 2019). Previous case studies have shown that the time period of structures significantly impacts the performance levels of concrete bridges under seismic loading. Single-column structures are more sensitive at larger time period values, but for all types, the displacement ductility is sufficient (Patil et al. 2019).

1.3.2 Dynamic methods

Dynamic Time History Analysis: Dynamic Time History Analysis (DTHA) is a commonly used method for analyzing the response of bridges to seismic and other dynamic loads. Here are the steps involved in DTHA of bridges:

- Identify the design earthquake ground motion: The first step in DTHA is to select a set of earthquake ground motion records that are appropriate for the bridge site. These ground motions should represent the expected seismic hazard at the site.
- Develop a finite element model of the bridge: A finite element model is developed using computer software that takes into account the structural geometry, material properties, and boundary conditions of the bridge.
- Apply the earthquake ground motions: The selected ground motion records are then applied to the finite element model to simulate the dynamic response of the bridge.
- Perform time history analysis: Time history analysis is performed to evaluate the dynamic response of the bridge at various locations and components, such as piers, abutments, and decks. This analysis involves solving the equations of motion using numerical methods to obtain the displacement, velocity, and acceleration responses of the bridge.
- Evaluate the bridge response: The results of the time history analysis are then evaluated to determine the maximum response values, such as peak displacements, velocities, and accelerations, and the corresponding locations and components of the bridge.
- Compare the response with the design criteria: Finally, the response values are compared with the design criteria and codes to assess the safety and adequacy of the bridge under the design earthquake ground motion.

DTHA is a complex and computationally intensive method that requires specialized software and expertise. It is important to use appropriate ground motion records, accurate finite element models, and reliable analysis techniques to obtain realistic and meaningful results.

An article discusses a method to determine damage fragilities for various damage states, such as column failure, concrete cover spalling, and buckling of bars, using the Dynamic Time History (DTH) approach. The fragility of bridge damage is defined by equations (Mackie and Stojadinovi 2007), which link ground motion uncertainty and median intensity to distinct damage states. In a study, damage fragility equations were established for earthquake intensities measured in both horizontal and vertical directions of the bridge using spectral acceleration (S_a) (Mackie and Stojadinovi 2007) (Pang et al. 2014). Similarly, using the same DTH method, seismic evaluation of a cable-stayed bridge with three super-tall towers was carried out (Wei et al. 2021).

Wei et al. (2021) observed that the cable restraint and horizontal fluid viscous damper could mitigate damage in a cable-stayed bridge with a combined middle tower and side floating towers, with the fluid viscous damper being more effective (Wei et al. 2021). The displacement components, particularly the bearings, of a cable-stayed bridge with super high piers and multi pylons were found to be more vulnerable when using Peak Ground Motion as an Intensity Measure (IM), and the transition piers were more susceptible to earthquakes (Wei et al. 2020). Rubber bearings, not pier columns, are typically the governing factor for the seismic behaviour of tall pier bridges exposed to near fault ground motions, and bearing failure should be considered in structural analysis Guo et al. (2022) (Chen 2020). Rezaei et al. (2020) found that foundations and piers are the most critical components when subjected to seismic ground motions in bridge structures. Earthquake incidence angle had a more significant effect on the foundation than on the ductility of elastomeric bearings in columns, but changing the regularity level of the bridge did not significantly affect the response sensitivity to the earthquake incidence angle (Rezaei et al. 2020).

Ren et al. (2019) concluded that a V-shaped continuous girder bridge with an 80-degree V angle exhibits good seismic capacity, with a PGA (Peak Ground Acceleration) of 0.8 g (Wei et al. 2021). Tolentino et al. (2020) proposed a methodology for extracting fragility curves for RC (Reinforced Concrete) bridge structures using the dynamic time history analysis method. The accumulated damage due to ground movements is determined by considering the maximum drift, and the method is validated through numerical analysis on a reinforced concrete continuous bridge in Mexico City (Tolentino et al. 2020) (Tolentino et al. 2020). Different drift limits are investigated to assess the likelihood of exceeding them, and the proposed method emphasizes the importance of considering the accumulated damage effect in seismic sequences (Tolentino et al. 2020). The effect of skew angle on the response of bridges under seismic action was investigated using nonlinear time history analysis and probabilistic seismic assessment (Yang et al. 2015).

The vulnerability of bridges with large skew angles was found to be higher compared to straight bridges, regardless of their seismic design or retrofitting status (Karim and Yamazaki 2003). Damage index, a parameter that represents the strength of the structure, was used to establish the connection between fragility curve parameters and the strength of RC bridge piers (isolated and non-isolated) through dynamic time history analysis, and its limits were presented in Table 1 (Karim and Yamazaki 2003). In the United States, six types of skewed bridges were studied to investigate the effect of skew angle on the seismic behaviour of bridges, including retrofitted bridges with column jackets and isolator bearings, properly seismically designed bridges, and non-seismically designed bridges (Yang et al. 2015). Formulas that consider the effect of skew on fragility curve parameters were developed for each bridge class and component type at different limit states. The probabilities of column damage can be reduced by seismic design and retrofitting of columns, without overstraining other bridge components, which results in lower bridge system risk compared to non-seismically designed bridges (Yang et al. 2015).

The column retrofits known as IB&KP, SE&SK, and RC&SK, are effective in reducing transverse and longitudinal bearing demands, but not column damage probabilities (Yang et al. 2015). A study was conducted to evaluate the performance of Triple Friction Pendulum System (TFPS)-isolated skew bridges under near-fault ground motions (Chauhan et al. 2017). The study considered Skew Bridges with intervals of 10° ranging from 0° to 50°. The responses of the bridges were analyzed in the direction along the length of the bridge under different near-fault ground motions (Chauhan et al. 2017). Results showed that TFPS was effective in decreasing the effect of skew angle in isolated bridges compared to non-isolated bridges. TFPS isolators were found to be very effective in reducing the impact of skew angle on the structure (Chauhan et al. 2017).

Four bridge types were defined based on an investigation of typical CSUS bridges, with the authors reporting that the peak ground acceleration required for a 50% chance of mild damage ranged from 0.19 to 0.24 g for these bridge types (Choi et al. 2004). The multi-span continuous steel-girder and simply-supported bridges were found to be the most vulnerable types (Choi et al. 2004). Bridges in pristine locations were found to have high resilience values, which decreased gradually over time as the bridge aged 30 to 60 years (Sharanbaswa 2011). A study developed a methodology to determine the earthquake resistance of RC bridge piers affected by reinforcing steel corrosion due to chloride content, using the same dynamic time history analysis method as before (Sharanbaswa 2011). However, further studies are required with improved corrosive modelling to replicate better actual bridge degradation caused by corrosion. In another study, deck displacement was calculated using non-linear time history analysis with two scaled ground movements (0.54 g) for HDRB and FPS, and the use of viscous dampers was found to greatly reduce bridge displacement due to ground acceleration, with centre deck displacement in FPS reduced to a maximum of 30% during every earthquake (Anandh and Ajisha 2018). To avoid significant movement of the bridge deck, bridge specifications should require anti-dislodgement devices, such as links or cables, and shear keys (Anandh and Ajisha 2018).

In this study (Billah and Todorov 2019), it was observed that the stiffness of lead rubber bearings (LRBs) increases at low temperatures, leading to a reduction in displacement ductility. Seismic fragility curves were developed for different bridge components, including bearings, piers, and the entire bridge. The results showed that bridge piers and bearings are more susceptible to damage at subfreezing temperatures than in summer conditions. Additionally, the dissipation energy in LRB isolation bearings decreases at subfreezing temperatures.

Incremental Dynamic Analysis: In order to conduct Incremental Dynamic Analysis (IDA) on a structure, it is necessary to have a representative earthquake record. This record can either describe the expected earthquake motion beneath the structure or be obtained from a non-linear response history analysis, which can simulate the response of any structure to an earthquake. The time history method can be used for both elastic and inelastic analyses, where the structural stiffness remains constant during the earthquake. However, in the inelastic analysis, stiffness is considered continuous only during incremental time steps. By analyzing the non-linear response history, sets of demands can be generated to predict the structure's performance. These sets are used to develop calculations that include median values and the spread of each desired parameter and to find correlations between different requirements in the set.

Recently, the parametric analysis method of IDA has emerged in various forms to estimate structural performance under seismic loads. IDA involves running multiple complex model analyses against a set of ground motion data, each of which is restricted to a different degree of seismic intensity. The levels are chosen to force the structure across the continuum action, from linear to plastic, and finally to strong ground motion variability, even as the structure experiences a collapse. Post-adjustment results in IDA curves for each record of earthquake magnitude, usually expressed by Intensity Measure (IM), comparison to structural response, as calculated by the Engineering demand parameter (EDP). Possible IM choices are scalar (or vector irregular) values relative to the intensity of observed ground motion and measured linearly or non-linearly according to its amplitude. IM is chosen carefully to produce the necessary hazard curves for centuries-old risk analysis. Conversely, IM should be followed by a structural response interest to minimize the amount of response analysis needed. Ground speed acceleration and high ground speed are options, but the most widely used spectral acceleration has damping of 5% during the first structure mode.

A comprehensive seismic fragility analysis technique incorporating the Incremental Dynamic Analysis method is utilized to evaluate the seismic performance of irregular bridges (Shan et al. 2020). Three distinct limit state equations are employed to characterize three types of earthquake risks in structural reliability theory, including pier biaxial shearing and bending vulnerability (Shan et al. 2020). The limit state function for bearing distortion is also determined (Shan et al. 2020). Fragility curves are then utilized to illustrate how the severity and direction of ground motion affect the fragility variations of various components (Shan et al. 2020).

Considering that a bridge's lifespan duration influences seismic damage, a study creates FEM models of a cable-stayed bridge with a single pylon and a large deck, while accounting for concrete carbonization (Li et al. 2021). During three-directional seismic waves, the pylon's base is the most vulnerable feature (Li et al. 2021). Carbonization can cause a 23% and 16% reduction in steel and concrete strength, respectively. This study establishes the strain limit for reinforced steel and concrete, as displayed in Tables 2 and 3 (Li et al. 2021).

This paper presents the results of the fragility curve development for two sample bridges that underwent seismic retrofitting by steel jacketing of bridge columns (Kim and Shinozuka 2004). The dynamic responses of the bridges before and after retrofitting were investigated using Non-Linear Monte Carlo simulation (Kim and Shinozuka 2004). Fragility enhancement due to the retrofit was quantified by comparing the fragility curves of the bridges before and after the retrofitting (Kim and Shinozuka 2004). Kim

Table 2 Strain reduction of reinforcement and concrete during the service life of cable-stayed bridges (Rezaei et al. 2020)

Sr. No	Strain limits	% Decrease during their service life
1.	Yield Strain of Reinforcement	6.43
2.	Ultimate Strain of Reinforcement	33.57
3.	Peak Strain of Concrete	25.33
4.	Crushing Strain of Concrete	28.40

Table 3 Seismic demand enhancement of FRC piers for a different types of fibres

Fibre type	Seismic demand enhancement
Steel fibres	20–30% (increment in ductility)
Polypropylene fibres	10%
Brittle FRC	15%

and Shinozuka reported that fragility curves are characterized by lognormal distribution functions and are produced as a function of PGA (Kim and Shinozuka 2004). The empirical curves were updated to apply to fragility curves based on damage from the Northridge earthquake (Kim and Shinozuka 2004). The predicted fragility curves after the steel jacketing retrofitting showed significant improvement (less fragility) compared to before the retrofitting (Kim and Shinozuka 2004).

The seismic vulnerability of a three-span continuous highway bridge located in Kishoreganj, Bangladesh, was evaluated in a study by Kabir et al. (2019). The study utilized the non-linear IDA method to analyze the bridge's response to medium to strong far-field, near-fault, and long-duration ground motions, and fragility curves were generated. The dynamic study used 48 different ground motion records with PGA ranging from 0.08 g to 2.31 g. A 3-D FEM technique was employed to account for nonlinearity in elastomeric isolation bearings and bridge piers. Fragility curves were established for the isolation bearings, bridge pier, and the entire system. Additionally, the study revealed that long-duration ground motions have a greater impact on the failure of the bridge system and components than far-field and near-fault ground motions.

A research conducted by Bayat et al. (2017) explores the seismic behaviour of continuous deck skewed bridges from various angles (Bayat et al. 2017). They use an Incremental Dynamic Analysis (IDA) method to develop fragility curves by running 20 records. The paper shows the four possible earthquake orientations and compares the Peak Ground Acceleration (PGA) and Spectral Acceleration (S_a) with damping of 5% and periods T_1 and T_i to find the optimal Intensity Measure (IM) for skewed highway bridges. The study highlights the importance of identifying the strongest earthquake. The findings indicate that Sa (T_1, 5%) is a competent IM for less than 5% of the observed data. Among the four orientations, the horizontal direction (-45°) is deemed to be the most critical, while the vertical direction (-45°) is somewhat less significant.

In a research by Jeon et al. (2019), a comparison is made between the seismic vulnerability of bridge columns with and without flares (Jeon et al. 2019). Numerical models are calibrated using existing experimental data for the columns with and without flares. The presence of flares in bridge columns increases their strength and stiffness, reducing the probability of column shear failure and therefore reducing the vulnerability of the bridge. Fragility curves are developed for four types of bridge column layouts: (1) one-way flared columns along the bridge transverse direction, (2) prismatic oblong column cross-sections, (3) two-way flares along both the bridge transverse and horizontal directions, and (4) flared columns with a gap of 102 mm between the flare top and superstructure. The study concludes that bridges with a flare gap perform similarly to those with prismatic columns, making it a viable retrofitting option to change the behaviour of flared columns.

In his study, Pang et al. (2020) utilised fragility functions to evaluate the seismic behaviour of bridge piers under both far-field and near-fault ground motions, considering both brittle and flexural failure modes at different levels of damage (Pang et al. 2020). The accuracy and reliability of the Cloud Analysis method were compared with IDA using force-based and deformation-based Engineering Design Parameters (EDPs), as proposed by Pang et al. Additionally, fragility curves were generated for FRC (Fiber Reinforced Concrete) piers reinforced with different fiber types to investigate their effectiveness in improving the seismic response of bridge piers. Fragility curves were also developed for the piers of the FRC bridge. The study found that near-fault ground motions increase seismic demands by approximately 5% for FRC piers and 10% for RC piers during far-field earthquakes. Table 3 shows the percentage increase in seismic demand for FRC bridge piers reinforced with different fibers.

Response spectrum analysis: In seismic research and design, access to historical data is crucial, but it is impractical to have all this information readily available. The peak value of ground acceleration (PGA) alone is insufficient for determining a structure's response to earthquakes. Factors such as the frequency content of ground motion and dynamic structural characteristics must also be considered. Consequently, the earthquake response spectrum is one of the most commonly used tools in seismic analysis, despite being costly. Compared to other methods of predicting displacements and member forces in structural systems, the response spectrum approach is more effective. However, it can only estimate displacements and member forces in each vibration mode using smooth design spectra that represent the average of numerous seismic movements rather than the lowest possible values. This paper will explore the response spectrum technique in-depth and its application to a wide range of structural systems.

In order to conduct a response spectrum analysis, certain factors must be taken into consideration, as outlined in the IS:1893 (Part 1)-2002 (Bureau of Indian Standards New Delhi 2002) code. This code outlines the requirements for response spectrum analysis and accounts for these factors. When an SDOF system is subjected to an earthquake ground motion, the maximum response of the system and the time period during which that response occurred are correlated with a response spectrum diagram (or frequency). The response spectrum represents the point at which the system exhibits the highest possible response for a given damping ratio. By analyzing the distribution of responses, the maximum structural responses that occur within a linear range of values can be identified using response spectra. These responses can then be used to determine the lateral forces generated in a structure during an earthquake, which is crucial for designing earthquake-resistant structures in the future. Parameters that affect response spectral

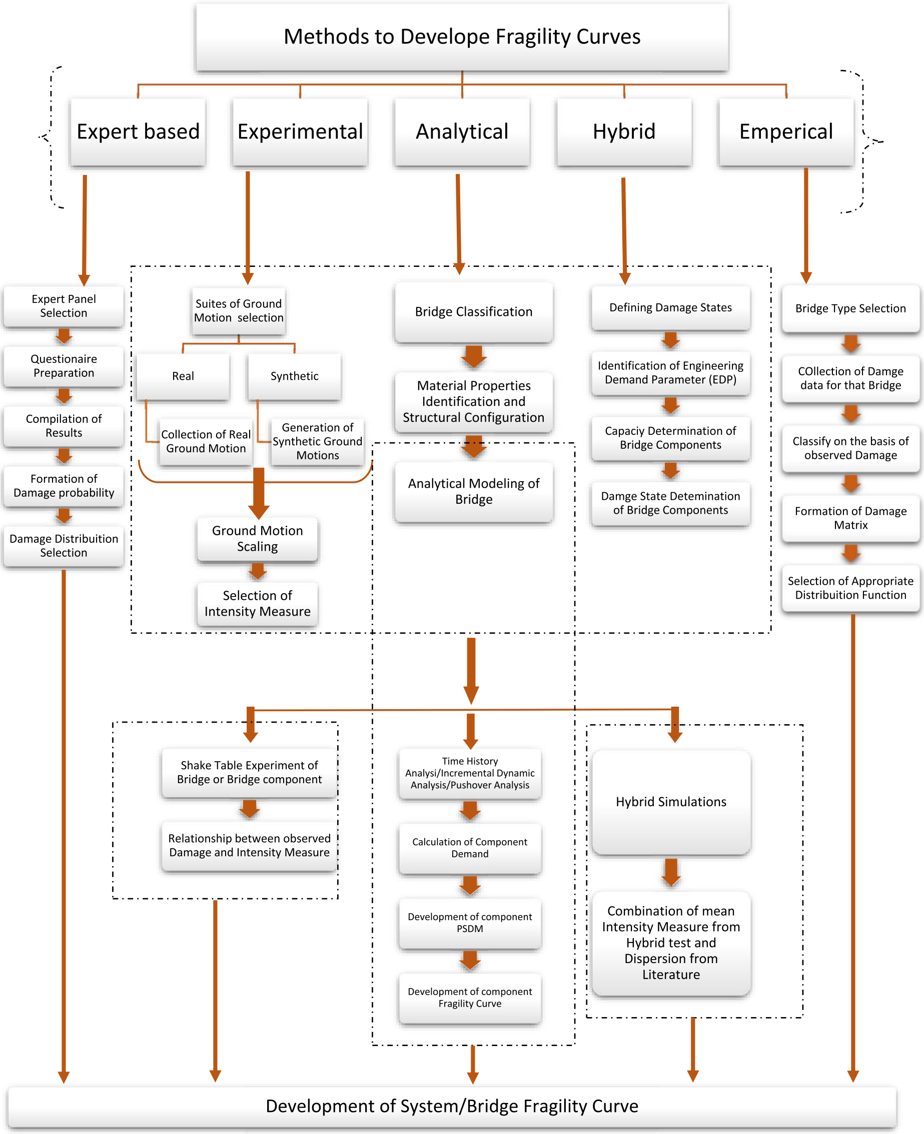


Fig. 6 Methods to derive fragility curves

values are Distance from the epicentre, Condition of soil, Focal depth, Time Period, Richter Value, and Damping.

2 Categories of fragility models

Over the last 20 years, the development of Fragility Curves has shifted from empirical to analytical methods. Researchers have utilized a variety of methodologies and techniques to create fragility curves, including analytical models, hybrid methods, and field studies. This section offers a concise overview of the diverse approaches utilized by researchers to evaluate the seismic susceptibility of bridges. Figure 6 shows various methods/approaches to derive fragility curves.

The Expert- or Judgemental-based method is a straightforward approach to derive Fragility Functions. The first step is to gather a panel of earthquake engineering experts to assess the various components of a typical highway bridge and predict the damage distribution when exposed to earthquakes of different intensities. A series of questionnaires are then used to survey the specialists. Next, the Probability distribution function is updated based on expert judgement to represent a specific damage level at varying levels of ground motion intensity. Finally, as the expert panel assesses each damage state, the Fragility curve for each state of damage can be generated.

To construct empirical fragility curves, damage distributions from the event are combined with post-earthquake field observations or reconnaissance reports. While empirical fragility curves provide a more realistic picture, their value is limited due to a high degree of inconsistency. There is a considerable increase in uncertainty in the generated curves because of variations in damage state definitions and observational differences across various inspection teams, which reduces the utility and trustworthiness of the empirical vulnerability curves.

The selection of statistical models is a crucial step in the process of fragility modeling. This involves choosing an appropriate probability distribution that can accurately describe the vulnerability of a system to damage or failure under different levels of hazard intensity.

The most commonly used statistical models for fragility analysis include the lognormal, Weibull, and beta distributions. The lognormal distribution is often used when the fragility of a system is influenced by multiple factors, such as age, material properties, and exposure to environmental conditions. The Weibull distribution is commonly used for systems that exhibit wear and tear over time, such as mechanical systems. The beta distribution is often used when the fragility of a system is affected by a combination of discrete and continuous factors, such as the presence or absence of safety measures.

When selecting a statistical model for fragility analysis, it is important to consider the characteristics of the system being studied and the nature of the hazard being modeled. The choice of distribution should also be supported by empirical data or expert judgment, and should be validated through statistical tests and sensitivity analyses. Overall, the selection of an appropriate statistical model is a critical step in the process of fragility modeling, and can have a significant impact on the accuracy and reliability of the results.

The methods of parameter estimation or fitting are essential to obtaining accurate and reliable fragility estimates. Once a statistical model has been selected for fragility analysis, the parameters of the distribution must be estimated based on available data or expert judgment.

Maximum likelihood estimation (MLE) is one of the most commonly used methods for parameter estimation in fragility analysis. MLE involves identifying the values of the distribution parameters that maximize the likelihood of observing the data that has been collected. This method is often used when there is a sufficient amount of data available and when the distribution parameters can be estimated independently.

Bayesian estimation is another common method for parameter estimation in fragility analysis. This method involves specifying a prior distribution for the parameters and then updating the prior based on the available data. Bayesian estimation is often used when there is limited data available or when the distribution parameters are interdependent.

Other methods of parameter estimation or fitting include moment estimation, which involves matching the first few moments of the distribution to the available data, and regression analysis, which involves using a linear or nonlinear regression model to estimate the distribution parameters based on predictor variables. Regardless of the method used for parameter estimation or fitting, it is important to validate the results through sensitivity analyses and statistical tests. This helps to ensure that the estimated parameters are robust and can be used to generate reliable fragility estimates.

Generating fragility curves for bridges through experimental data is not a common approach due to the high costs involved in conducting large-scale experiments with full-scale components or whole bridge models. Instead, researchers have mainly relied on analyzing the response of structures to shaking table testing. Although experiments can provide valuable information for developing damage measures, the lack of sufficient data limits their usefulness. The limitations of traditional methods, such as a shortage of actual earthquake damage data, subjective data, and deficiencies in analytical procedures have also hindered fragility curve development. Hybrid fragility curves, which combine different methods to address these limitations, have been proposed as a solution to improve the accuracy and reliability of fragility curves for bridges.

As discussed earlier, fragility analysis refers to the probability of a structure sustaining damage during seismic events or its service life. Several methodologies outlined in this chapter can be employed to assess the fragility of any structure, which can be categorized based on the degree of damage. In addition, various techniques are available to determine damage states, such as historical damage data collected in the field, expert opinion, laboratory testing, and numerical simulations (Todorov and Billah 2021). The mathematical representation of fragility is depicted in Eq. 1, which is a cumulative lognormal distribution function that depends on the demand (drift, displacement, or ductility) at a specific damage state.

$$F(DS) = \varphi\left[\frac{ln(Ds) - \theta}{\beta}\right] \tag{1}$$

Equation 1 expresses the fragility for a specific damage state, where "F(DS)" represents the cumulative distribution function, ϕ denotes the standard cumulative distribution function, and the parameters β and θ represent the lognormal standard deviation and median values of that damage state, representing the median and standard deviation of the logarithm of the demand variable (e.g., drift, displacement, or ductility) at the specific damage state.

3 Fragility analysis of newly constructed and retrofitted bridges

Fragility analysis is a type of analysis that is used to evaluate the susceptibility of a structure to damage or failure under various conditions. When it comes to newly constructed and retrofitted bridges, fragility analysis plays an essential role in ensuring that these structures are safe and resilient to natural and man-made hazards.

Here are some of the key factors that are typically considered in fragility analysis of newly constructed and retrofitted bridges:

- Seismic hazard: Bridges are designed to withstand seismic forces, but the level of seismic hazard varies depending on the location of the bridge. Fragility analysis considers the expected seismic hazard at the bridge location to determine how the structure will perform during an earthquake.
- Wind loads: Wind loads can cause significant damage to bridges, especially during extreme weather events. Fragility analysis considers the expected wind loads at the bridge location to determine the likelihood of damage or failure.
- Flood hazard: Bridges that are located near water bodies are susceptible to flood damage. Fragility analysis considers the expected flood hazard at the bridge location to determine the likelihood of damage or failure during a flood event.
- Construction quality: Fragility analysis also takes into account the quality of construction and the materials used in building the bridge. Newly constructed bridges are subjected to more rigorous testing and inspections to ensure that they meet the required standards.
- Retrofitting measures: If an existing bridge has undergone retrofitting measures to enhance its resilience, fragility analysis considers the effectiveness of those measures in improving the bridge's performance during an extreme event.

Overall, fragility analysis plays a crucial role in ensuring that newly constructed and retrofitted bridges are resilient to various hazards and can withstand extreme events, providing safe and reliable infrastructure for transportation and commerce.This section provides an overview of seismic studies that have employed Fragility Analysis to examine various types of bridges and their components, presented in the following sections, namely 3.1, 3.2, and 3.3.

The publications referred to in this manuscript were analyzed by year and typology, as shown in Figs. 7 and 8. Approximately 50% of the selected papers were published

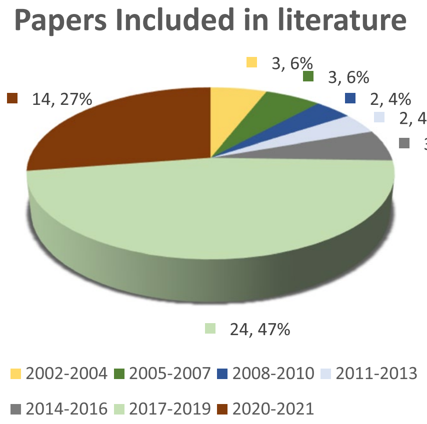


Fig. 7 Year-wise referred publications

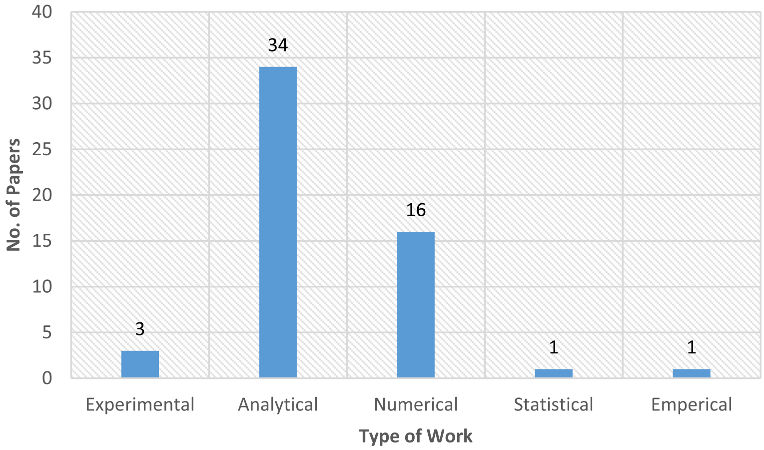


Fig. 8 Adopted typologies in the referred literature

between 2017 and 2019, indicating a peak in research on the fragility analysis of structures during these years.

Regarding the adopted typologies in the referred literature, most researchers used analytical and numerical approaches to study the fragility of structures. In contrast, experimental, statistical, and empirical approaches were used less frequently. Figure 8 provides a visual representation of these trends.

3.1 Fragility analysis on retrofitted bridges

Bridges constructed prior to 1980 without retrofits experienced significant damage due to ground movement, which was a frequent occurrence. Most of the strategies for causing damage to bridges were observed in previous seismic events. To prevent bridge collapse and deck unseating during the 1995 Kobe earthquake, seismic retrofitting of existing bridge piers designed according to pre-1980 standards has become a top priority. During the 2011 Great East Japan Earthquake, the earth movement caused multiple retrofitted bridges to sway. Elastomeric bearings are an effective retrofit measure for reducing minor damages in bridges, especially for steel and concrete girder bridges (Padgett and DesRoches 2009). Different retrofit measures serve different functions in preventing damages. For some bridge types, seat extenders are the most effective in reducing the probability of complete damage and are also cost-effective (Padgett and DesRoches 2009). Such as shear keys were practical for continuous bridges rather than simply supported ones (Padgett and DesRoches 2009).

Research examined various retrofit solutions, including super elastic shape memory alloy (SMA) cables, friction dampers (FD), viscous dampers (VDs), and yielding steel cables (YSC) to reduce the seismic vulnerability of bridges (Xiang and Alam 2019). Fragility Analysis was used to evaluate the relative effectiveness of these devices in reducing damage occurrence to the isolation bearings without putting the bridge piers at risk (Xiang and Alam 2019). The study found that all devices were equally effective in reducing damage occurrence to the isolation bearings. However, SMAs were the most effective in reducing the bridge system's seismic vulnerability in all damage states, followed by VDs, YSCs, and FDs (Xiang and Alam 2019). This is because SMAs have superior self-centering capacity, resulting in better recentring results and less residual displacement of the superstructure than bridges retrofitted with other measures (Xiang and Alam 2019).

Several Caltrans bridges were severely damaged during the Northridge earthquake due to the lack of column jacketing. However, after retrofitting with steel jacketing, a study found a significant decrease in the number of damaged bridges, particularly for severe damage levels (Parghi 2016). Another study examined a cable-stayed bridge retrofitted with the passive control or "Menhsin Design" technique and highlighted the critical importance of accurately estimating structural elements' strength and stiffness thresholds, as they can significantly affect the fragility curve results (Casciati et al. 2008). Evaluating the impact of retrofitting requires considering the reaction quantity, component vulnerability, and overall bridge fragility (Baker 2007). The most effective retrofit strategy for reducing likely damage depends on the damage condition, such as using steel jackets for concrete girder bridges where columns are the primary element of fragility, and isolation for steel girder bridges (Padgett and DesRoches 2009). Engineered cementitious composites (ECC) and carbon fiber reinforced polymer (CFRP) jacketing show less susceptibility when exposed to diverse damage states during both near-fault and far-field earthquakes (Billah et al. 2013).

3.2 Fragility analysis of bridge piers

Recent earthquakes have highlighted the vulnerability of highway bridges located in earthquake-prone areas (Pang et al. 2020; Kawashima et al. 2008). Residual drift in bridge piers can lead to reinforced concrete (RC) highway bridges collapsing during strong earthquakes (Xiang and Li 2017). Figure 9 demonstrates a typical layout of deck slab bridge & its piers. Researchers have analyzed bridge piers hybridized with High Strength Reinforced Steel (HS-NS) and Shape Memory Alloy (SMA) reinforced steel bars using analytical simulations (Salkhordeh et al. 2021). They compared post-tensioned segmental bridge piers to monolithic ones to assess their development (Salkhordeh et al. 2021). The seismic performance of the HS-NS pier was found to be significantly better than that of the SMA-NS pier (Salkhordeh et al. 2021). Billah and Alam (Salkhordeh et al. 2021) noted that the demand parameter for displacement ductility indicated greater

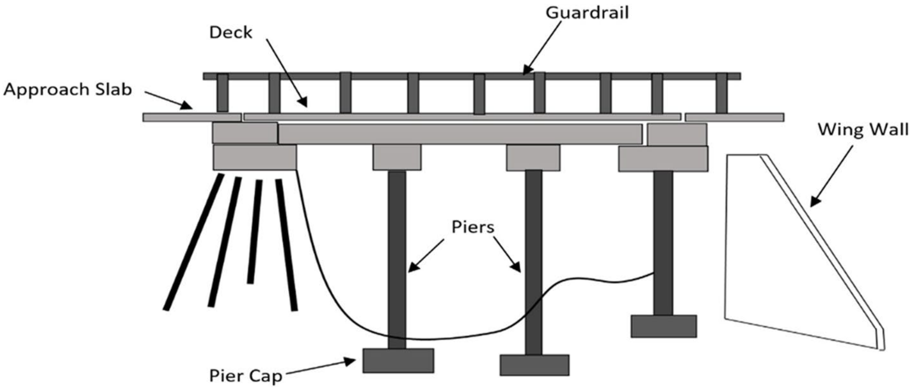


Fig. 9 Typical layout of a deck slab bridge

vulnerability in the plastic hinge area of the SMA-reinforced bridge pier, but the supplied parameter for displacement ductility did not.

When the residual drift is utilized as the EDP, the steel-RC bridge pier becomes more delicate, as reported in Billah and Alam (2015). However, in the plastic hinge region, SMA is used instead of steel rebars to improve post-seismic performance and decrease vulnerability in terms of performance requirements during an earthquake (Billah and Alam 2015). As a result, the SMA-RC bridge pier is less prone to damage than the steel-RC bridge pier (Billah and Alam 2015) (Tran et al. 2020). The seismic behaviour of steel girder bridges is considerably influenced by the pier height and cross-section. According to the study's findings, bridges with higher piers are more vulnerable to damage than those with lower piers.

Designing for earthquakes must also consider the possibility of short pier shear failures (Tran et al. 2020). Among various pier shapes, those built into walls are the most resistant to earthquakes, followed by rectangular and circular piers. To improve our understanding of the role of various uncertainties in the seismic fragility of the SMA-RC bridge pier, further research is needed using bridge piers of different shapes and material properties. Location and duration of ground vibrations are critical considerations in designing a bridge's seismic performance. Even when assessing different damage states, Near Fault (NF) motions, which are pulse-like, are typically more vulnerable to maximum drift than their long duration (LD) and far-field (FF) counterparts, regardless of the damage state studied (Todorov and Billah 2021). The bridge piers responded similarly to all three types of ground motion, up to a maximum drift of 3 per cent (Todorov and Billah 2021). However, NF motions tend to cause significant deformation at higher drift levels, as measured by the exact intensity measurement (Todorov and Billah 2021). To adequately capture the impacts of vibrations on infrastructure, there is a need to develop damage indices or quality measurements that can account for both the pulse and duration effects of ground vibrations. Furthermore, to better understand performance-based seismic design in the context of bridges, future research should investigate various factors, such as ground motion intensity measures, different bridge components and systems, demand parameters like residual drift, different bridge pier configurations, and soil-structure interaction (Todorov and Billah 2021).

In (Ren and Obata 2000), the authors estimated the behaviour of deteriorated bridge piers during their service life based on their time-variant capacity. They predicted the deformation capacity of the bridge columns by considering the plastic hinge length and found that the drift ratio significantly decreases with an increase in the corrosion level compared to the non-corroded state. The authors recommended further research on deteriorating bridge piers by considering actual corrosion patterns, such as pitting corrosion. In another study (Xiang and Li 2017), the performance of conventional and hybrid fiber reinforced concrete (HyFRC) piers was compared, and it was concluded that the limit state capacity of the HyFRC pier was higher than that of the conventional pier. The HyFRC pier was found to be less vulnerable across all damage states compared to the conventional pier.

3.3 Cable-stayed bridges

In recent decades, there has been a rise in the construction of cable-stayed bridges worldwide for various reasons, including their appealing aesthetics, efficient and rapid construction process, increased stiffness compared to suspension bridges, complete utilization of structural materials, and the relatively small size of bridge elements (Ren and Obata 2000). However, the collapse of several bridges during earthquakes, such as the 1995 Kobe earthquake, the 1999 Taiwan Chi-Chi earthquake, and the 2008 China Wenchuan earthquake, has raised public concerns about the seismic safety of these bridges. Due to their high flexibility and poor inherent damping, cable-stayed bridges are particularly vulnerable to earthquakes (Pacheco and Fujino 1993; Chang et al. 2004), which can result in many casualties and significant damage. Therefore, evaluating the seismic vulnerability of cable-stayed bridges at different damage levels is crucial to ensure their safety. According to a study (Cheng et al. 2019), the deck, cables, and expansion joints are more vulnerable in cable-stayed bridges with tall piers, while the failure probability of the pier is relatively low. They also concluded that the deck-pier connection is responsible for the increased stiffness in cable-stayed bridges. Figure 10 represents the typical layout of a cable-stayed bridge.

3.4 Skewed bridges

A study utilized Probabilistic Seismic Assessment and Non-Linear Time History Analysis to investigate the impact of skew angles on the earthquake response of bridges. It was found that bridges with larger skew angles are more susceptible to collapse compared to straight bridges (Yang et al. 2015). However, this policy only applies to bridges designed to withstand earthquakes. The study examined six types of skewed bridges, including those with non-seismically designed (NSD) columns, seismically designed (SD) columns, and those with four retrofits commonly used in the central and southeastern United States (CSEUS) (Yang et al. 2015). Regardless of whether the bridges were made of concrete or steel, the skew angle increased their reactivity, whether they were seismically designed or not, or had undergone renovations. Fragility curves for systems with straight or skewed angles showed a wider range in median fragility parameters compared to consecutive curves, making them more complex. The skew angle does not have

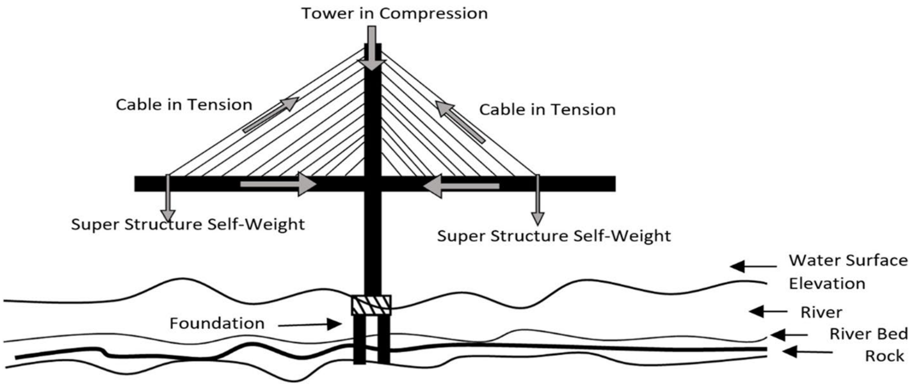


Fig. 10 Typical layout of a cable-stayed bridge

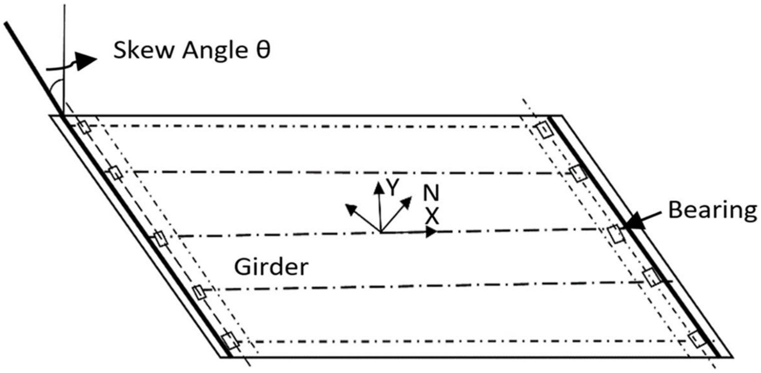


Fig. 11 Schematic representation of deck for a skewed bridge

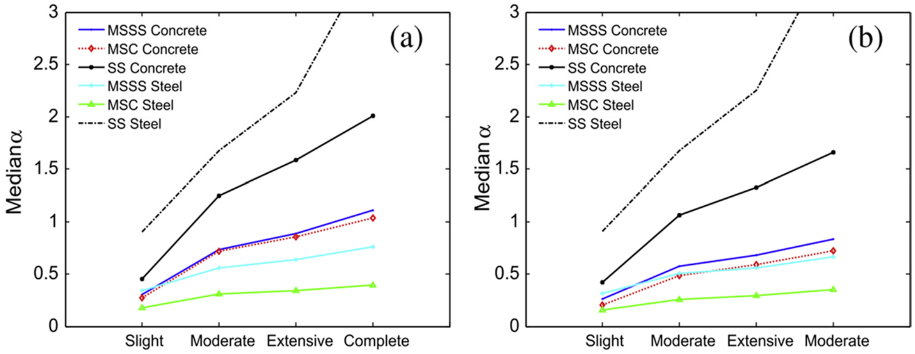


Fig. 12 Comparison of median fragility values for six bridge types: (**a**) straight bridges; and (**b**) 30° skewed bridges (Yang et al. 2015)

a linear relationship with the difference increment. Figure 11 illustrates the schematic representation of deck for a skewed bridge.

The analysis of system fragility curves for the six types of non-seismically designed (NSD) bridges indicates that the weakest bridge type, both with and without skew, is the Multi-Span Continuous (MSC) steel bridge, followed by the MSC concrete, MSC concrete with skew, Single-Span (SS) concrete, and SS steel bridges (Pang et al. 2014). Furthermore, the fragility curves of MSC steel and MSC concrete bridges are similar due to the sensitivity of steel bearings compared to elastomeric bearings used in concrete bridges. Additionally, single-span concrete and steel bridges, which have no columns and experience reduced seismic stresses on their bearings, are less vulnerable. For NSD MSC concrete and MSSS concrete bridges, skew reduces the median values of fragility to that of NSD MSSS steel bridges (Yang et al. 2015).

The fragility of six bridge types with and without a 30° skew angle is presented in Fig. 12, which displays the median values for the four limit states in the median state. Among all six types, the (Multi-Span Continuous) MSC steel bridge type exhibits the lowest median value for all limit states, indicating it to be the weakest. This is due to high demands on columns and non-ductile bridge components such as steel expansion bearings. The order of strength for the remaining five bridge types, from strongest to weakest, are the Multi-Span Simply Supported (MSSS) steel, Multi-Span Continuous (MSC) concrete, and the Multi-Span Simply Supported steel bridges as shown in Fig. 12(a). Figure 12(b) shows that MSSS and MSC concrete bridge types for skewed bridges are similar to MSSS steel bridge types.

4 Discussion

Earthquakes can cause significant damage to bridge structures, which makes the seismic behaviour of bridges a critical area of research. The performance of bridges during seismic activity is impacted by several factors, such as the type of bridge, its structural characteristics, the intensity of the earthquake, and the characteristics of the ground motion. Therefore, this study aims to delve into these variables and determine their effects on different types of bridges, such as simply supported, continuous, concrete, and steel bridges.

The ultimate goal of this study is to identify measures that can mitigate the seismic effects on bridge structures, thereby enhancing their performance during an earthquake. Previous research has highlighted a significant gap in research related to the fragility analysis of bridges situated in hilly areas. Therefore, this study will specifically focus on exploring the seismic behaviour of bridges located in hilly areas to understand the unique challenges that these bridges face and develop measures to mitigate the impact of seismic activity on these structures.

Apart from the gap in research, previous studies have identified several limitations in the current design codes. For example, there is no check on the maximum allowable displacement for bridge piers in the current design codes, which can lead to a higher likelihood of collapse for taller piers during an earthquake. To ensure that bridge structures can withstand seismic activity, component-level seismic assessments must be conducted during the design of new structures. Therefore, this study aims to address these limitations and provide recommendations to reduce the risk of bridge collapse during an earthquake.

Overall, the findings from this study can inform future design and construction practices for bridges, which can enhance their seismic performance and ensure the safety of people and infrastructure during an earthquake. A comprehensive understanding of the factors that influence the seismic behaviour of bridges is crucial for designing and building bridges that can withstand seismic activity and reduce the risk of catastrophic failure. The results of this study could also help in developing more efficient and effective retrofitting measures for existing bridges to improve their seismic performance.

5 Conclusions

In conclusion, the seismic behaviour of bridges is a critical area of research due to the significant damage that earthquakes can cause to these structures. Understanding the factors that influence the seismic behavior of bridges is crucial for designing and building bridges that can withstand seismic activity and reduce the risk of catastrophic failure, ensuring the safety of people and infrastructure during an earthquake. Followings are the key concusions of this study:

- This study identifies the effects of various variables on different types of bridges, such as the type of bridge, structural characteristics, and earthquake intensity.
- Focusing specifically on bridges located in hilly areas, the study addresses the research gap related to the fragility analysis of these structures and develop measures to mitigate the impact of seismic activity on them.
- It addresses limitations in the current design codes, such as the lack of a check on the maximum allowable displacement for bridge piers, which can lead to a higher likelihood of collapse during an earthquake.
- The findings of this study could help in developing more efficient and effective retrofitting measures for existing bridges.
- A comprehensive understanding of the factors that influence the seismic behavior of bridges is crucial for designing and building bridges that can withstand seismic activity and reduce the risk of catastrophic failure, ensuring the safety of people and infrastructure during an earthquake.

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Authors' contributions
The first author (KT) initiated the idea, designed the study, conducted a brief literature survey, scrutinized the literature, participated in sequence alignment, and prepared a draft copy of the manuscript. The second author (AR) has collected the data, scrutinized the literature, categorized them according to the sequence, participated in sequence alignment, and designed the graphics & illustratons. The third author (HG) participated in sequence alignment & coordination, and reviewed the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
Not applicable (As the manuscript is review-based; no furhter data would be required. However, if any literature data is required, first author would provide them).

Declarations

Competing interests
We would like to declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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