Introduction

Numerical methods are certainly the most important approach that allows for developing fragility curves. Such methods are particularly useful in the absence of adequate damage data and can be classified into three main approaches: (i) the elastic spectral analysis [1] (ii) the nonlinear static analysis$_a$ (see for instance [2], [3]) and (iii) the Nonlinear Time History Analysis (NTHA) (see for instance [4], [5]). The NTHA is the most rigorous method of assessment of the inelastic seismic demands of structures. Performance-based earthquake engineering (PBEE) requires a large amount of NTHAs to statistically evaluate the performance of RC structures. In order to accurately estimate the large inelastic responses of structures, the incremental dynamic analysis (IDA) [6], [7] is often used. This method is based on the NTHA performed using a suite of selected as-recorded or artificial ground motions at different hazard levels employing a well-calibrated finite element model. To study the full range behaviour of earthquake demands, the different hazard levels are set by adjusting the ground motion intensity measure (IM), such as PGA from elastic responses to structural collapses. By performing a series of NTHAs, IDA curves can be obtained, which expresses the relationship between the selected engineering demand parameters (EDPs) and IM of ground motions. This analysis is particularly advantageous to accurately predict the seismic demands of structures that are subjected to dynamic lateral loading during an earthquake. However, numerical modelling of the relevant nonlinear phenomena requires sophisticated constitutive material models to accurately simulate the nonlinear RC bridge response. Previous studies have focused on proposing advanced modelling techniques to model nonlinear response of RC columns including the effects of bar slip, bar buckling and low-cycle fatigue (e.g. [8], [9], [10], [11]). In fact, the use of advanced modelling strategy renders PBEE approach quite complex and particularly onerous to be applied beyond the research context.

The bar slip which is caused by the reinforcement slip in the column footing or beam-column joint regions could significantly affect the total lateral displacement of reinforced concrete (RC) members under lateral loading. According to experimental results, the deformation caused by the bar elongation at the member end can account for up to 40% of the total lateral displacement [12]. Several numerical investigations concerning the effect of the bond slip on the behaviour of RC columns have been carried out in the past. Nonlinear analysis results under monotonic [13] and cyclic loads [14], [15], [16] proved the importance of including the bar slip effects to the lateral displacement responses of RC columns. Moreover, the contribution of the strain penetration effect to the nonlinear dynamic analysis behaviour of the RC structures was addressed in [17], [18]. It is found that neglecting this effect in nonlinear analyses will significantly underestimate the deflection and overestimate the stiffness and hysteretic energy dissipation capacity. On the other hand, the bar buckling of vertical reinforcing bars is recognised as an important phenomenon that can significantly affect the response of RC elements, especially at the final stage of inelastic response [19], [20], [21], [22]. This phenomenon is more significant when using high-strength reinforcements [11]. This is particularly due to the fact that using high-strength material as reinforcement in RC columns will result in relatively smaller bar diameters and greater stirrup spacing, which results in a more flexible reinforcement caused by the reduction of the reinforcement stiffness. Moreover, experimental investigations carried out on RC columns have indicated that buckling of reinforcing bar is often accompanied by a fracture of the longitudinal reinforcement due to low-cycle fatigue damage [12], [23], [24]. Recently, it was experimentally observed that the inelastic buckling is one of the key parameters affecting the low-cycle fatigue life of reinforcing bars which may cause premature fracture of longitudinal reinforcement due to the low-cycle high amplitude fatigue degradation [25], [26]. According to experimental and numerical investigations, RC bridge piers constructed with high-strength steel bars have lower low-cycle fatigue and ductility performance compared to that constructed with conventional steel bars, which is particularly problematic for RC bridge piers in highly seismic regions [27]. In fact, higher yield strength steel increases elastic deformation, but decrease plastic deformation, which may have significant influence on the strain demands of longitudinal bars. More recently, Su et al. [28] evaluated the effects of bar buckling and low-cycle fatigue on seismic performance of RC piers constructed with high-strength steel bars through fragility analysis. They found that using hight-strength steel bars to replace conventional steel bars by equal strength replacement tend to increase the deformation demands in terms of maximum drift by about 5%. This was attributed to the decrease of post-cracking stiffness observed particularly for lower reinforcement ratio. It was also found that replacement of conventional steel bars by equal volume replacement is more effective to prevent the bar buckling and low-cycle fatigue effects, as the RC piers constructed with hight-strength steel bars show similar deformation demands in terms of maximum drift, but significantly less section damage.

Section snippets

Objective and methodology

Most of the current analytical researches on the bar slip, bar buckling and low-cycle fatigue are focused on studying the nonlinear response of the RC structures under seismic loading without considering the uncertainties associated with seismic inputs and structural capacity. This paper addresses this gap by using seismic fragility assessment procedures based on fragility analysis. This approach takes into account the uncertainties in seismic hazards and structural capacity, but more

Case study RC bridge pier configurations

The bridge piers studied here is part of a previous experimental program [12], [29], [30]. This program was undertaken to assess the seismic performance of RC bridge columns that experienced ductile flexural response. The RC bridge pier is a single circular column, as shown in Fig. 1. The columns had one-third of full scale of the most typical layouts of well-confined RC bridge piers currently in use in regions of high seismicity in the United States. In this paper, six representative

The finite element modelling strategy

The finite element model is established using the Open System for Earthquake Engineering Simulation (OpenSees) program [32], which is an open-source finite element computer code. The RC bridge piers are simulated using nonlinear beam-column element with fibre-defined cross-sections which is a line element that allows the calculation of the nonlinear response at selected locations (also known as integration points) along the member length from the fibre section assigned to that location. The

Seismic performance of RC bridge piers

The main objective of this section is to investigate the sensitivity of the analytical results to the inclusion of bar slip, bar buckling and low-cycle fatigue degradation of vertical reinforcement. Both cyclic and monotonic nonlinear pushover analyses are considered. For comparison purposes, the analyses are carried out for different calculation options (refer to Table 1 for the list of calculation options), whereas the material models for concrete, reinforcement steel and zero length element

General

In this section, the dynamic responses of RC bridge piers obtained from IDA are discussed, highlighting the sensitivity of the results to the inclusion of the most relevant effects discussed in Section 5.4. In order to develop the IDA curve, the PGA is selected as IM. PGA has already been proved to be both an efficient and a sufficient IM for the seismic performance assessment of RC bridge columns (e.g.[56], [57]).

Nevertheless, this choice is particularly suitable because it is more convenient

General

The fragility curves represent the conditional probabilities that the structural damage lies in or exceeds a particular level of damage state (ds) under seismic excitation with various intensities. In the present study, the PGA is adopted as the intensity measure (IM), thus the fragility curve is expressed as a function of PGA for a particular damage state, ds, by P [DS ≥ ds | PGA]. The damage states (DS) of the bridge components can be measured from different forms of EDPs, for instance,

Conclusions

This research work focused on the seismic assessment of RC bridge piers - dominated by flexure - accounting for individual and combined effects of bar slip, bar buckling and low-cycle fatigue. Five numerical models with different material properties were created to evaluate their effectiveness in a performance-based earthquake engineering analysis. Moreover, six well confined RC circular bridge columns with different configurations were considered. Comparative performance-based assessment based

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.