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Influence of Earthquake-Tsunami Sequence Induced Corrosion on Residual Seismic Capacity of Concrete Structures

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ABSTRACT

Field investigations have highlighted the high likelihood of chloride ingress in reinforced concrete (RC) buildings submerged by seawater and covered by mud during an earthquake-tsunami (EQ-TS) sequence. Chloride attack through EQ-induced cracks or spalling can cause a high corrosion rate in the reinforcement, thereby compromising the long-term durability of the structure and its performance in future events. Typically, this deterioration process is neglected when assessing the future performance of frame structures in tectonically-active coastal regions. This study demonstrates the influence of EQ-TS-induced corrosion on the residual seismic capacity of modern RC frame structures. The analyses show an undesirable component-level failure mode switch to a shear-dominated mechanism. The median collapse fragility of the frame is also seen to be significantly influenced by the reinforcement corrosion. The outcome of this study raises questions on the post-tsunami management of both modern and older-type RC frame structures.

Introduction

Structures in coastal regions close to tectonically active zones are susceptible to cascading hazards. Recent global events (e.g., 2010-2011 Christchurch earthquake sequence, New Zealand; 2011 Tohoku Earthquake, Japan; 2018 Central Sulawesi Earthquake, Indonesia) have demonstrated the impact of sequential hazards such as mainshock-aftershock (MA-AS) and ground shaking-tsunami (EQ-TS) sequences. In some instances, the long-term effect of cascading hazards may result in increased life-cycle costs for structures, even when these have seismic detailing. For example, corrosion assessment studies on RC buildings submerged by the 2004 Indian Ocean and 2011 Tohoku have shown a continuous increase in corrosion levels of the reinforcement [1,2]. In such cases, while the structures did not suffer significant damage from the EQ-TS sequence, TS-induced seawater and mud penetration into the EQ-induced cracks were observed to cause extensive deterioration of the structural components. Consequently, RC structures that suffer chloride penetration from the tsunami attack will have an increased maintenance cost over their remaining life. It is well known that reinforcement corrosion in RC structures can occur due to chemical attack (for certain building uses) and from the use of contaminated (unwashed) aggregate in the concrete mix. However, the increased rate of corrosion in RC structures subjected to EQ-TS sequences is currently ignored. Hence, the current study investigates the effect of chloride-ion penetration on the long-term seismic behaviour of RC frame structures in coastal regions close to tectonically active zones.

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This study incorporates information about corrosion-induced time-varying material- and component-level deterioration of concrete structures into a time-dependent probabilistic framework to assess the influence of TS-induced corrosion on the residual seismic capacity of RC structures. In this paper, the methodology is demonstrated using a modern seismically designed RC frame structure.

Time-dependent probabilistic framework

In this study, the performance-based earthquake engineering framework is modified to incorporate tsunami analysis and time-dependent corrosion-induced degradation of structural capacity. The proposed framework for assessing the influence of TS-induced corrosion on the residual seismic capacity of civil infrastructure is presented in Figure 1. The corrosion rate function for EQ-TS damaged components (in Figure 1) accounts for chloride ingress through EQ-induced cracks. Hence, the adopted corrosion rate function differs from existing models, which mainly consider diffusion through concrete cover [3] and may not applicable in this case. Further information on the development of corrosion rate function and other aspects of the methodology is provided elsewhere [4].

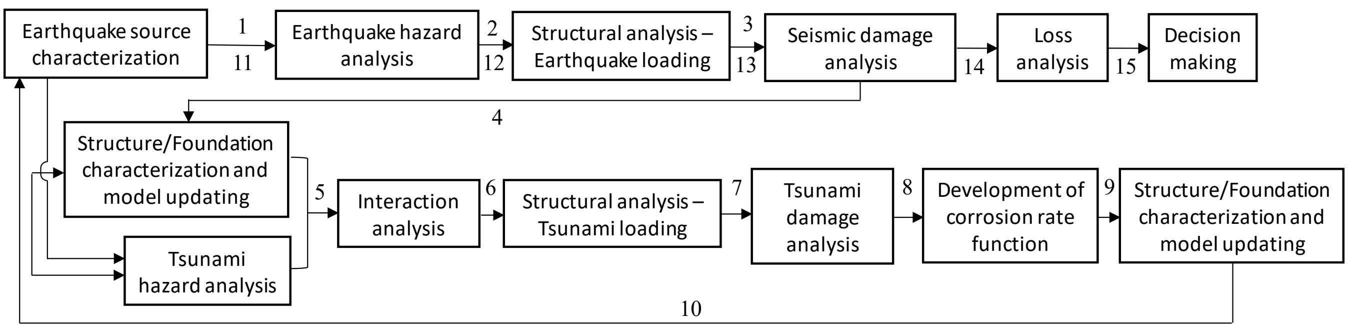


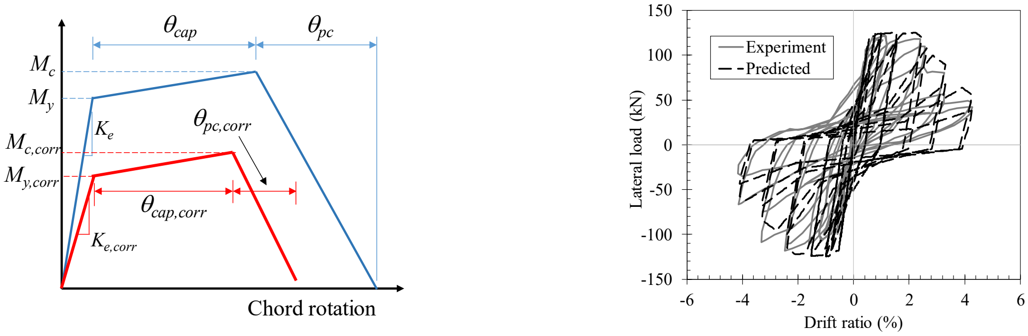
Figure 1. Framework for corrosion-inducing EQ-TS sequence

Numerical Modelling of Corroded Components

The cyclic response of corroded components can be modelled following the failure-mode-based approach [5]. Recommendations on capturing the influence of corrosion level on the force-displacement and hysteretic behaviour of concrete components [4]. The proposed methodology can be adopted for fibre-element and lumped plasticity modelling techniques. For the sake of brevity, discussions here focus on the lumped plasticity approach. Figure 2a depicts the backbone of a pristine component and the corrosion-induced backbone degradation for a corroded component. As shown in Figure 2a, the proposed approach can capture the influence of corrosion-induced concrete softening and/or EQ-induced cracking on the initial stiffness of the corroded components. Figure 2b compares the measured and predicted cyclic response of a corroded code-conforming beam that suffered a corrosion-induced flexure-shear failure (test data from [6]). Apart from accurately predicting the failure mode of the corroded component, the methodology adequately captures the cyclic behaviour of the component. Further discussions are provided in [4].

Case Study

The case study building is a modern four-story frame structure located at a hypothetical coastal seismically active site (Figure 3a) . A 2D model of one of the frames of the structure was modelled using OpenSees [7]. The seismic mass of the frame was lumped at each beam-column joint, the floor diaphragms were assumed rigid, and the ground floor columns were assumed to be fixed at the foundations. The beams and columns of the structure were modelled using a combination of elastic beam-column elements and zero-length nonlinear rotational springs as described in [4]. The beam-column joints are modelled implicitly per ASCE/SEI 41-17 [8]. To account for geometric nonlinearity effects, a P-delta formulation was employed. The fundamental period of the structure is 1.1sec.



(a) Backbone of pristine and corroded component (b) Comparison of experiment and predicted response

Figure 2. Modelling the cyclic behaviour of corroded beam-column components

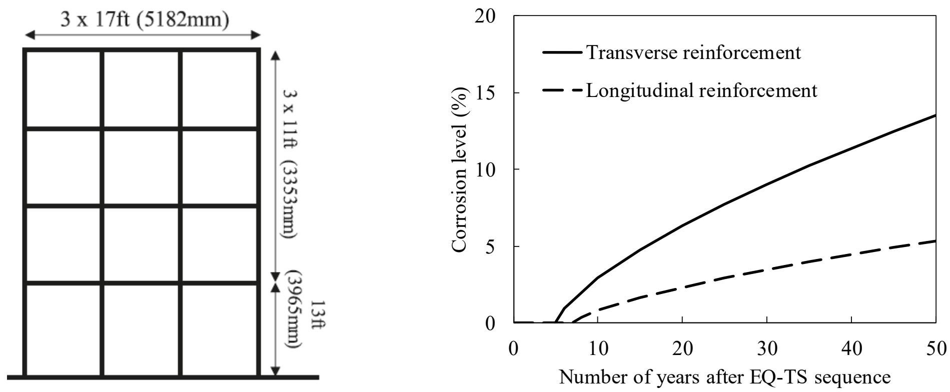
Following the proposed framework, the frame was initially subjected to a back-to-back EQ-TS time history analysis. The EQ record was selected from a suite of 11 records, scaled using the conditional mean spectrum approach [9], to a site-specific seismic hazard spectrum with S_{XS} = 0.62g and S_{X1} = 0.3g (corresponding to hazard level with a 20% probability of exceedance in 50years). The tsunami time history was developed in accordance with ASCE 7-16 [10] using tsunami inundation parameters (inundation depth of 4m and velocity of 2.5m/s) at the building site, determined using the Energy Grade Line Analysis (EGLA). Following the procedure outline in Figure 1, after the back-to-back EQ-TS time history analysis was conducted, damage analysis of the beam-column components was carried out. The damage analysis concluded that the damage states of the beam-column components could be classified as slight (i.e. based on component drift demands). Using the corrosion rate model described in [4], which accounts for the influence of EQ-induced residual cracks, the corrosion level in the longitudinal reinforcement with respect to time was estimated (Figure 3b).

In this study, based on the assumption that the EQ-TS induced chloride ingress was not treated, two long-term scenarios were considered – Scenario 1 (1S), where the chloride ingress from the seawater induced localized corrosion in the beam and column reinforcement of the first story only; and scenario 2 (2S) where the chloride ingress induced localized corrosion in beam and column reinforcement of the first and second stories. In both scenarios, the condition of the upper floor beam-column components was assumed to be pristine.

In total, five variations of the frame structure were considered – a pristine frame with no corrosion (PF), a scenario 1 frame after 25years of EQ-TS sequence (1S25), a scenario 1 frame after 50years of EQ-TS sequence (1S50), a scenario 2 frame after 25years of EQ-TS sequence (2S25), and a scenario 2 frame after 50years of EQ-TS sequence (2S50). The corroded beams and columns of the structure were modelled using lumped plasticity models, accounting for corrosion effects as described previously in this paper.

The collapse response of each frame variation was assessed through incremental dynamic analyses (IDA), using a suite of 22 pairs of recorded far-field ground motions from FEMA P-695 [11]. Global collapse capacity was defined to correspond to the smallest scaling of a ground motion sufficient to achieve either a maximum inter-story drift of 10% or axial failure in 50% of columns on any floor.

Collapse fragility functions were developed for the five frame variations using the IDA results. Figure 4 depicts the variation of the median collapse spectra acceleration at the fundamental period ($S_a(T_1)$) with respect to the number of years after the EQ-TS sequence. As shown in Figure 4, the corrosion level (i.e. related to the number of years after EQ-TS) and distribution of corrosion along the building (i.e. scenario 1 or 2) has a significant influence on the collapse fragility of the building. The reduction in collapse capacity of the corroded buildings was mainly due to a switch to a shear-dominated mechanism as a result of transverse reinforcement corrosion. As shown in Figure 4, if not controlled, EQ-TS induced chloride attack may lead to up to 40% long-term decrease in collapse fragility of modern buildings.



(a) Elevation (b) Corrosion level in reinforcement

Figure 3. Case study building

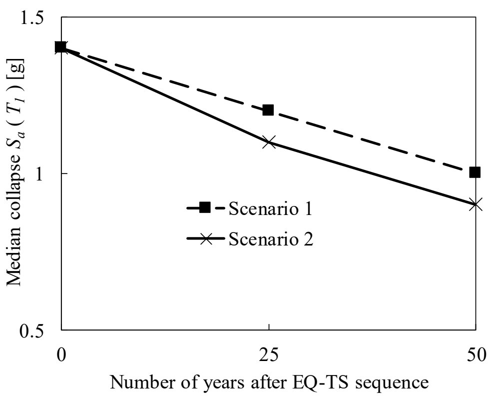


Figure 4. Influence of corrosion-induced deterioration on collapse fragility of considered frame

Conclusions

This study provides an overview of a proposed methodology for assessing the residual seismic performance of buildings damaged by earthquake-tsunami (EQ-TS) events. The methodology accounts for an increased corrosion rate in concrete components due to EQ-induced residual cracks. The methodology was demonstrated using numerical modelling of a modern RC frame structure that suffered slight damage from an EQ-TS event. The results showed that EQ-TS induced chloride attack may lead to up to a 40% long-term decrease in collapse fragility of modern buildings. The reduction in collapse fragility is attributed to corrosion-induced reinforcement degradation and undesirable failure mode switch to a shear-dominated mechanism. Based on the outcome of this study, it is recommended that chloride attack preventive measures may be required as part of any post-EQ-TS management framework.

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