A FRAMEWORK TO QUANTIFY THE CUMULATIVE DAMAGE DUE TO INDUCED SEISMICITY

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ABSTRACT

A framework for assessing the potential for cumulative damage on bridges due to a large number of small-to-moderate induced earthquakes is presented. The method is based on rainflow counting per the ASTM standard practice for cycle counting in fatigue. A quantitative measure – Fatigue Damage Index (FDI) – is proposed and developed using Miner's Rule to identify the accumulated damage in the bridge, from which the remaining service life can be estimated. The FDI can also be used to predict when accelerated repairs may be required and to evaluate accelerated retrofit solutions.

INTRODUCTION

States such as Oklahoma, Texas, Kansas and Arkansas historically have experienced only one or two tectonic earthquakes annually prior to 2009, but these states are now experiencing earthquakes at an increased rate due to induced seismicity; see Figure 1(a). Consequently, State Departments of Transportation (DOTs) are concerned about how their bridges, which were originally designed for low seismic design loads, will handle this increased seismic demand (1). While a structural collapse is unlikely for an induced earthquake (2,3), cumulative effects of large number of small induced earthquakes compounded with an occasional moderate earthquake may lead to damages negatively impacting the safety of the traveling public and the flow of the transportation network. This research addresses the knowledge gap on the effects of low-level frequent earthquakes on the bridges and proposes a framework to assess the cumulative damage on bridges. In the following section, the framework is presented, along with a demonstration of its use in Oklahoma.

THE THEORETICAL FRAMEWORK

The proposed framework aims to evaluate the potential for cumulative damage (high-cycle fatigue) in bridges caused by many small-to-moderate induced earthquakes. To this end, the framework characterizes the cumulative cyclic demand on a structure for a desired set of ground motion data and compares the demand against the capacity of the structure to assess the likelihood of fatigue. A new metric, the *fatigue damage index* (FDI), is used to quantify the proportion of the fatigue life that is accumulated and can estimate the remaining service life of the structure. The FDI framework is illustrated in Figure 2 and is comprised of six steps described in the following sections.

Step 1 – Mathematical Model of the Bridge

The first step of the FDI framework is to develop a mathematical model of the bridge of interest—either a "typical" bridge or a specific bridge. This model is used to determine the natural modes of vibration for the structure. Assuming that the structure has two axes of symmetry subjected to bi-directional horizontal GM along these axes, then the modal responses in the longitudinal and transverse directions can be treated independently. Furthermore, it is assumed that a single (fundamental) mode in each direction of response is sufficient. The natural period T_m in either direction can be determined by either some approximate method or modal analysis. To this end, the model may be quite simple or very detailed, depending on the application.

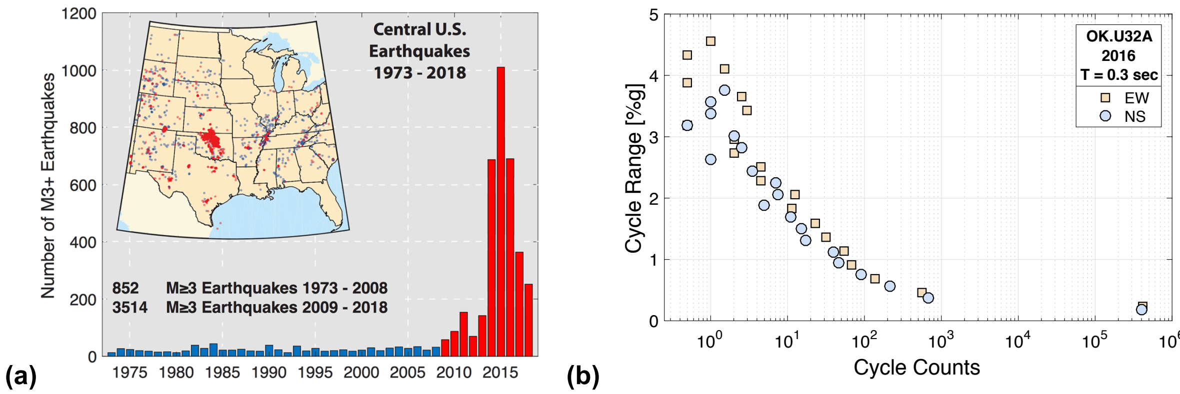

Figure 1: (a) Annual number of earthquakes with a magnitude of 3.0 or larger in the central and eastern United States, 1970–2016. Source: USGS (4). (b) Pseudo-acceleration cycles for the response of simple harmonic oscillator (ζ=5%) with period T = 0.3 s subject to the EW and NS components of all the ground-motion accelerations measured at station OK.U32A in 2016.

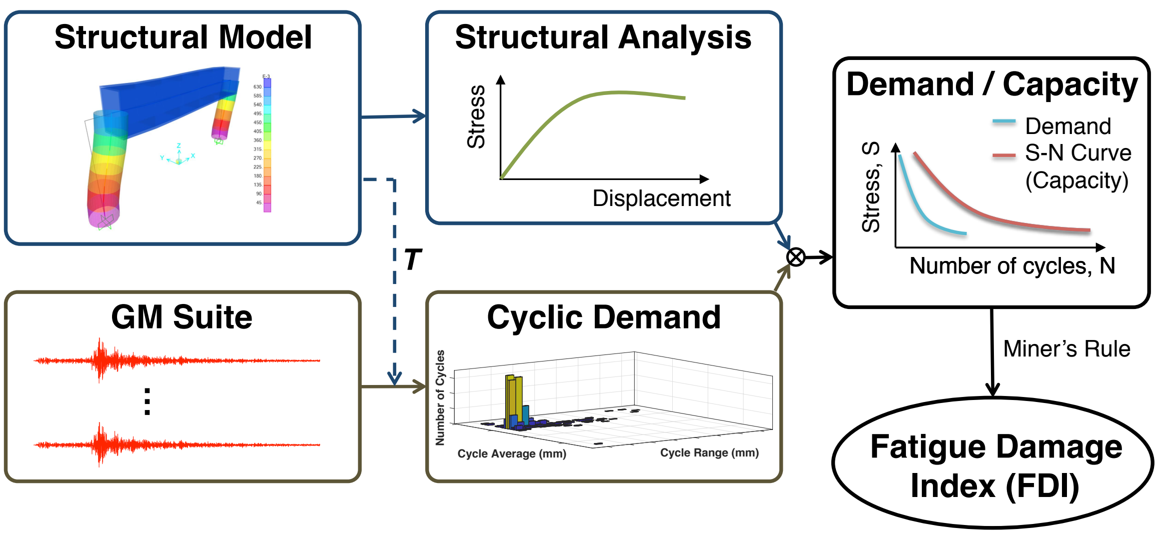

Figure 2: Framework for calculating the Fatigue Damage Index (FDI).

Step 2 – Compile Ground-Motion Data

The next step is to compile and organize a sequence of ground motions (GMs) impacting the bridge during the time frame of interest (e.g., one calendar year) and in the desired range of earthquake magnitudes (e.g., greater than some threshold). The GM sequence S is composed of N bi-directional (EW and NS) horizontal GMs. Because GM measurements are taken at seismic stations that are most likely not collocated with the bridge of interest, seismic stations should be selected to be roughly representative of the seismic hazard at the bridge's actual site.

Step 3 – Characterize the Cyclic Seismic Demand

To quantify the cyclic seismic demand, simple harmonic oscillators representative of the bridge are subjected to the sequence S of earthquake ground motions acquired in Step 2. For each oscillator, the displacement response is computed independently for the two components of horizontal GM (EW and NS). The cyclic seismic demand is characterized in terms of cycle counts at set of displacement cycle ranges (denoted D_k) using the rainflow counting algorithm (5). The displacement cycle counts are converted to pseudo-acceleration cycle counts (Figure 1(b)) by the relationship $A_k = (2\pi/T_m)^2 \times D_k$. Cycle counts in the EW and NS directions are combined by taking the square root of the sum of their squares (SRSS).

Step 4 – Structural Analysis for Earthquake Loading

In this step, the pseudo-acceleration cycle ranges A_k are related to stresses at certain locations in the bridge deemed critical. Equivalent static earthquake loading are determined using one of the two single-mode methods of analysis per AASHTO (i.e., single-mode spectral method or uniform load method), where A_k/g replaces the elastic seismic response coefficient, C_{sm}. From the ensuing analysis, the seismic force effects at each pseudo-acceleration cycle range A_k are related to stress cycle ranges f_k within the bridge.

Step 5 – Demand-to-Capacity Analysis

In this step, the demand on and capacity of the bridge are combined with one another to determine the potential for fatigue. The demand is characterized by the stress cycle counts and ranges determined in Step 4. The capacity of the particular structural element of interest is characterized by the material's S-N curve. An S-N curve represents number of cycles to failure at each cyclic stress level for a given material and is specific to the test configuration used in fitting the curve. One must identify appropriate S-N curves for the material based on the *in situ* loading conditions. To compare the demand and capacity, Miner's rule (6) is used: $C = \sum(n_k/N_k)$ where C is the damage fraction and n_k (demand) and N_k (capacity) are the number of cycles at stress range f_k. Damage fractions in the longitudinal (C_l) and transverse (C_t) directions are combined using SRSS to give the *fatigue damage index*, FDI = $(C_l^2 + C_t^2)^{1/2}$.

CONCLUSIONS

In this paper, a quantitative measure (FDI) and a framework for its application were presented. The method uses Miner's Rule to identify the potential for accumulated damage in a bridge caused by a large number of induced earthquakes, from which the remaining service life can be estimated. The FDI can also be used to predict when accelerated repairs may be required and to evaluate accelerated retrofit solutions.

ACKNOWLEDGEMENT

This material is based upon work supported by the Accelerated Bridge Construction University Transportation Center (ABC-UTC). This support is greatly appreciated.

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