Optimal Retrofit Scheme for Highway Network under Seismic Hazards

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ABSTRACT
Many older highway bridges in the United States (US) are inadequate for seismic loads and could be severely damaged or collapsed in a relatively small earthquake. According to the most recent American Society of Civil Engineers’ infrastructure report card, one-third of the bridges in the US are rated as structurally deficient and many of these structurally deficient bridges are located in seismic zones. To improve this situation, at-risk bridges must be identified and evaluated and effective retrofitting programs should be in place to reduce their seismic vulnerabilities. In this study, a new retrofit strategy decision scheme for highway bridges under seismic hazards is developed and seamlessly integrate the scenario-based seismic analysis of bridges and the traffic network into the proposed optimization modeling framework. A full spectrum of bridge retrofit strategies is considered based on explicit structural assessment for each seismic damage state. As an empirical case study, the proposed retrofit strategy decision scheme is utilized to evaluate the bridge network in one of the active seismic zones in the US, Charleston, South Carolina. The developed modeling framework, on average, will help increase network throughput traffic capacity by 45% with a cost increase of only $15million for the Mw 5.5 event and increase the capacity fourfold with a cost of only $32m for the Mw 7.0 event.

Keywords: Retrofit, Seismic hazards, Optimization, Highway network

1. INTRODUCTION
Many highway bridges in the United States (US), in particular older bridges that predate modern seismic code provisions, are inadequate for seismic loads and could be seriously damaged or suffer collapse in a relatively moderate intensity earthquake [1].
On the most recent infrastructure report card issued by the American Society of Civil Engineers (ASCE), one-third of the bridges in the US are deemed structurally deficient [2]. Since the 1960’s, major structural damage has occurred to highway bridges due to earthquakes, which caused millions of dollars of economic losses in various states, such as Alaska, California, Washington, and Oregon [1]. To improve this situation, at-risk bridges must be identified and evaluated and retrofitting programs should be in place to reduce the seismic vulnerability [1]

Retrofitting all at-risk bridges is neither practical nor economical. Thus, it is important for the transportation stakeholders (e.g., the federal/state departments of transportation or DOT) to determine what to do in order to maximize the benefit (e.g., maintaining functional post-disaster traffic conditions) on the retrofit expenditures [3, 4]. The retrofit decision making is challenging, which is essentially a resource allocation problem under uncertainty [5]. The first challenge is that the resources, including budget, human resources, and material supplies are all limited. The second challenge is attributed to the inherent uncertainty associated with predicting future seismic hazards. The future cannot be predicted with certainty, so this uncertainty is transferred to the retrofit decisions.

Currently, the Federal Highway Administration (FHWA) uses the expected damage method and the indices method to determine the priority for retrofitting bridges. The expected damage method compares the severity of expected damage for each at-risk bridge and the bridges with the highest expected damage will receive the highest priority for retrofitting [1, 6]. The indices method uses indices to characterize the structure vulnerability and hazard level of the bridge [1]. These indices are then combined to generate a rating from 0 to 10 for each bridge, and are used to determine the priority for retrofitting. These methods provide quantitative results on the expected damage and direct economic losses; however, these two methods do not consider the crucial effects of traffic networks on highway bridges. The bridge failures or even capacity reductions may redistribute the traffic to the entire network. Thus, the bridge retrofit strategy solely based on the severity of expected damage of individual bridges may not lead to optimal solutions from the system perspective [7]. Therefore, a system-level retrofit decision scheme, which explicitly considers the performance of retrofitted bridge network, should be considered.

The traffic network effects have been incorporated in optimization model based retrofit strategy designs, such as [8-12] or in emergency evacuation planning, such as [13]. Due to the large scale of traffic networks and the complexities in modeling the user equilibrium (UE) or system optimization (SO) traffic conditions [14], a compromised way to make the problem more tractable would be to simplify retrofit decision into a binary variable (i.e., either retrofit a bridge or not), and simplify the bridge damage condition into a binary parameter, which assumes a bridge is either undamaged or completely damaged/collapse. For example, Fan et al. [8] used binary retrofit decision variables and assumed binary bridge damage conditions in their optimization program for determining the best retrofit strategies for the highway bridges in the San Francisco Bay Area under seismic hazards. The SO condition was considered in [8]. The models in [9, 10] were similar to [8]; however, the UE traffic condition was assumed. Chang et al. [12] extended these assumptions to allow for a
set of mutually exclusive retrofit alternatives and explicitly considered the probability of damage states in their study to maximize the post-disaster network evacuation capacity. However, they only budgeted for the retrofit cost and neglected the subsequent bridge damage cost resulting from the retrofit strategies.

In this study, we aim to develop a cost-effective retrofit program that preserve maximum level of post-disaster (i.e., earthquakes) traffic flows of sending rescue resources, which explicitly integrates the expected damage severity and the adverse impact on the traffic network into the decision making scheme. Our analysis considers a full spectrum of bridge retrofit strategies that are based on explicit bridge structural assessments for each possible seismic damage state. The optimization model will indicate what retrofit strategy applies to which bridge. The goal is to minimize the total cost incurred by retrofitting the bridges and the subsequent expected damage cost, while maximizes traffic flows between source nodes and sink nodes without exceeding the capacity of any links in the network. It is important to note that both the expected damage and retrofit costs are included in the objective for achieving the overall cost-effective retrofit strategies, since a retrofit strategy that is low-cost in retrofitting may have high-cost damages in the aftermath of an earthquake. An empirical case study using full-scale, real-world bridge network data in Charleston, South Carolina is presented. The results indicate that on average the throughput traffic capacity is gone up by 45% with a cost increase of only $15m for the $M_{5.5}$ event and the network capacity will be increased fourfold with a cost of only $32m for the $M_{7.0}$ event.

The remainder of the paper is organized as follows. In section 2, we will discuss the bridge seismic damage states and the available retrofit strategies. The optimization program will be presented and discussed in section 3. In section 4, we will describe the data inputs for the network of Charleston case study, followed by numerical results with analysis. We conclude the study in section 5 and outline future possible research efforts.

2. BRIDGE DAMAGE EVALUATIONS AND RETROFIT STRATEGIES

In this section, we will summarize the possible seismic damages to the highway bridges and discuss in more details on the available retrofit strategies for the bridges.

2.1 Damage States

The consequences of damage sustained by a bridge during an earthquake can range from minor to severe. The impacts of a bridge collapse are clearly seen in the risk to safety and the monetary value needed to replace the bridge, while less severe damage has subtle but costly consequences. A bridge closure, even temporary, can have tremendous consequences as bridges often provide vital links in a transportation network. A closure of a bridge may impair emergency response operations in the aftermath of an earthquake and an economic impact that continually builds. The economic impact can increase with the length of time the bridge is closed, the economic importance of the traffic using the route, the traffic delay caused by following alternate routes, and the replacement cost for the bridge. In this study, we adopted five distinct damage states (i.e., none, minor, moderate, extensive and complete) as defined in the earthquake loss estimation technical manual of the HAZUS program (Hazards-United States) for bridges [15]. There are other software for assessing seismic damages,
including the REDARS\textsuperscript{1} (for Risks due to Earthquake DAmage to Roadway Systems), that accounts for the consequences of earthquake damage on post-event traffic flows and travel times, and their associated losses. For this study, the damages states in the HAZUS program are adopted and are described as follows:

- **None** (d0) – No Damage
- **Minor** (d1) – Minor cracking and spalling to the abutment, cracks in shear keys at abutments minor spalling and cracks at hinges, minor spalling at the column or minor cracking to the deck
- **Moderate** (d2) – Any column experiencing moderate cracking and spalling, moderate movement of the abutment, extensive cracking and spalling of shear keys, any connection having cracked shear keys or bent bolts, keeper bar failure without unseating rocker bearing failure or moderate settlement of the approach slab.
- **Extensive** (d3) – Any column degrading without collapse, significant residual movement at connections, or major settlement, vertical offset of the abutment, differential settlement at connections, or shear failure at abutments.
- **Complete** (d4) – Any column collapsing and connection losing all bearing support, which may lead to imminent deck collapse, or tilting of substructure due to foundation failure.

### 2.2 Bridge Retrofitting Strategies

The main bridge components to be considered under retrofit strategies are superstructure, substructure, and foundation. There are various seismic retrofit methods for bridges with varying effectiveness. These seismic retrofits typically focus on achieving one or more of the following objectives \cite{1}:

- strengthening bridge components
- improvement of displacement capacity
- limiting seismic forces on major bridge components
- modification of the bridge response
- site remediation by ground movement
- acceptance or control of damage to specific components

Bridge damage classifications and possible retrofit strategies are identified in the Seismic Retrofitting Manual for Highway Bridges \cite{16}. Four retrofit strategies considered in this model are defined as follows in addition to the “do nothing”.

- **Strategy 0 (S0): Do Nothing**
- **Strategy 1 (S1): Superstructure Retrofits**
- **Strategy 2 (S2): Superstructure and Substructure Retrofits**
- **Strategy 3 (S3): Superstructure, Substructure, and Foundation Retrofits**
- **Strategy 4 (S4): Complete Bridge Replacement**

**Nothing and Full Replacement Options**

When retrofitting a seismically deficient bridge, two possible solutions, at opposite ends of the spectrum, should be kept in mind: the ‘do-nothing’ and ‘full-replacement’ options.

\textsuperscript{1}More information is referred to https://mceer.buffalo.edu/research/redars/
The ‘do-nothing’ option requires the acceptance of damage during a future earthquake. This will be a relatively straightforward decision if the expected damage is not a threat to life safety [1]. The most likely cause of loss of life is total collapse of a span, but this is a relatively rare event. For example, the toppling or failure of individual bearings will not necessarily lead to collapse if the bearing seats are wide enough to catch the superstructure. Similarly, foundation failures are unlikely to cause collapse, unless the ground deformations are extremely large due to widespread liquefaction or massive ground failure such as fault rupture. Fortunately, these occurrences are rare. Nevertheless, judgment should be used when assessing collapse potential and to the extent possible.

The ‘full-replacement’ option, on the opposite, may be an attractive option, particularly when the cost of retrofit is on the same order of magnitude as the replacement cost of the bridge. Full replacement is generally considered whenever the retrofit costs approach 60 to 70 percent of a new bridge and may become even more attractive if the structure has non-seismic structural deficiencies and is functionally obsolete [1]. However, the cost of demolition and any costs associated with control and rerouting of traffic should be considered as part of the cost of the replacement alternative.

Superstructure Retrofitting
The most common and serious seismic deficiencies are often at the bearings and bearing seats, and can potentially lead to a loss of support and collapse of the bridge [1]. In order to prevent failure of bearing and expansion joints of a bridge several relatively simple and inexpensive actions can be taken. Retrofitting measures include restraining devices, bearing seat extensions, bearing strengthening, and bearing replacement. The main retrofit seen in this area is the use of restrainers to tie different parts of the bridge together [16]. The three main types of restrainers are longitudinal joint, transverse bearing, and vertical motion restrainers. Longitudinal joint restrainers are installed to limit the relative displacement at joints and decrease the chance of losing support or unseating at these locations. Transverse bearing restrainers are a necessity in most cases. They are designed to keep the superstructure from sliding off its supports if the bearings were to fail. Finally, vertical motion restrainers are designed to prevent uplift that could cause damage to the bridge.

If it is impractical to restrain the movement of the bridge to prevent losing support at bearings, additional retrofitting methods can be done. These include bearing seat extensions and replacing the bearing. Bearings should be replaced if their failure will result in collapse or loss of function of the superstructure. Replacing or strengthening bearings and their accompanying restraining components should be capable of resisting the longitudinal, transverse, and vertical forces acting on the bridge.

Substructure Retrofitting
Bridge substructure (columns and cap beams) retrofitting measures have been the subject of intensive research and development, leading to great insight into the effectiveness of different retrofitting strategies on the substructure of bridges [1, 17]. For example, columns are commonly deficient in flexural ductility and shear strength. A significant portion of the initial column research provided insight into the effectiveness of different retrofit measures to improve both flexural and shear strength, and flexural ductility of reinforced concrete bridge columns [18]. As a result, standards were developed for evaluating bridge columns and standard techniques were adopted.
for improving their ductility and shear resistance [19]. This was accomplished by encasing reinforced concrete columns in circular or elliptical steel shells (steel jacketing) or by wrapping them with fiber composite materials. These methods were shown in the laboratory to improve flexural ductility and shear strength and to prevent the failure of starter bar splices located within potential plastic hinge zones. They have now been implemented on a large number of California bridges, and been proved to be effective in practice by preventing several bridge failures during the 1994 Northridge earthquake [20].

Steel jacketing significantly improves the flexural strength of the column by using passive confinement. Two steel plates are placed around the area to be retrofitted and the gap in between is filled with concrete adding support to the column. Composite fiberglass/epoxy wrapping has been successful in enhancing the flexural ductility and shear strength of columns. Similarly to steel jacketing, the composite fiberglass/epoxy wrapping is wrapped around the critical areas of the column [16].

Foundation Retrofitting

Abutments, footings, and foundations connect the bridge to the earth, and are the means by which a bridge feels the effects of an earthquake. Most foundation failures that occur during earthquakes can be attributed to the instability of the supporting soil due to liquefaction, lateral spreading, fault movement, or landslide [1]. Very few bridges have collapsed due to structural failure of foundation components, but there are instances where retrofitting is required.

Footings that support columns may be structurally unable to resist the forces transmitted from those columns. This usually occurs when there is a lack of reinforcement in the top of the footing [1]. Structural strengthening of the footing will be necessary to force plastic hinging into the column. There are also cases when movements of existing footings can result in instability of the pier and the capacity of the pier foundations needs to be increased. Instability caused by liquefaction or lateral spreading can also be addressed by providing strong foundations [1]. Retrofitting footings is the most expensive aspect of bridge seismic upgrading. Deficiencies are found in flexural strength, shear strength, footing/column shear strength, anchorage of column rebar, pile capacity, and overturning resistance. Retrofitting strategies include overlaying of reinforced concrete, increasing the depth of the footing, and prestressing by drilling ducts or new concrete on the sides [16].

3. OPTIMAL RETROFIT DECISION MAKING FRAMEWORK

We develop an optimization program to determine the best bridge retrofit strategies, with the lowest total expenditures on retrofitting bridges and the subsequent expected damage cost. Let \( G = (V, A) \) be a highway network, where \( V \) is the node set and \( A \) is the link set. The nodes denote junctions or interchanges on the roadway network. We denote by \( O \) the set of source nodes and \( R \) the set of sink nodes on the network, and thus \( O, R \subseteq V \). As bridges are part of the highway system, thus the set of bridge, denoted by \( I \), is a subset of link set, i.e., \( I \subseteq A \). Denote \( K(h, j) \subseteq A \) as the set of links that constitute a path connecting nodes \( h \) and \( j \), denoted by \( (h, j) \), \( \forall h, j \in V \) on the network. For example, if a path \( (h, j) \) is consisted of three links \#1, 2, and 3, we denote by \( K(h, j) = \{1, 2, 3\} \).
In this research, the probability of a bridge experiencing a damage state \( d \in D \) (where \( D \) denotes the set of aforementioned possible damage states) relates to the geographic location \( i \in I \) and the retrofit strategy \( s \in S \) (where \( S \) denotes the set of aforementioned possible retrofitting strategies). The probability of bridge \( i \) with retrofit \( s \) experiencing damage state \( d \) under an earthquake scenario is denoted as \( P_{dis} \), and \( \sum_{d \in D} P_{dis} = 1 \), \( \forall i \in I, s \in S \). We use the scenario-based seismic analysis [21] with two earthquake scenarios to evaluate the impacts of damaging earthquakes on the bridge traffic capacity. The selected earthquake scenarios (magnitudes and location of epicenters) correspond to the maximum credible earthquakes (MCEs), expected from each source [21].

It is challenging to estimate the retrofit and recovery costs, which are interdependent. A more retrofitted bridge network with higher resilience against seismic hazards will require lower recovery efforts, vice versa. Thus, the retrofit decisions should be evaluated in both terms and included in the single objective. In this research, we assume that the retrofit cost is as a percentage (denoted as \( \eta_s \)) of the new construction or replacement cost (denoted as \( CR_i \)). We further assume that the bridge damage cost due to the seismic hazards is linearly proportional to the traffic capacity loss, denoted by \((1 - \rho_d)\) where \( \rho_d \) is the remaining traffic capacity of a bridge after an earthquake. The assumed bridge remaining traffic capacities \((\rho_d)\) under damage states \( d_0 \) through \( d_4 \) are respectively 1, 0.8, 0.6, 0.2, and 0.

A mixed integer linear programming model was formulated to minimize the total cost of retrofitting bridges and the expected damage cost while meeting a prescribed system-level traffic capacity. The model will explicitly determine retrofit strategies on the network of bridges. The complete model is provided in (1)-(8).

\[
\text{Minimize } \sum_{i \in I} \sum_{s \in S} CR_i \eta_s x_{is} + \sum_{d \in D} \sum_{i \in I} \sum_{s \in S} (1 - \rho_d) CR_i P_{dis} x_{is} \quad (1)
\]

Subject to

\[
\sum_{d \in D} \sum_{i \in I} P_{dis} = F \quad (2)
\]

\[
\sum_{i \in I} \sum_{s \in S} x_{is} = 1 \quad (3)
\]

\[
\sum_{i \in V} f_{kj} = \sum_{j' : (k,j') \in E} f_{k j'} \quad \forall k \in V \quad (4)
\]

\[
f_{kj} \leq \min_{i \in K(h,j)} C_i \sum_{d \in D} P_{dis} \rho_d x_{is} \quad \forall h,j \in V \quad (5)
\]

\[
\sum_{s \in S} x_{is} = 1 \quad \forall i \in I \quad (6)
\]

\[
x_{is} \in \{0,1\} \quad \forall i \in I, s \in S \quad (7)
\]

\[
f_{kj} \geq 0 \quad \forall h,j \in V \quad (8)
\]
Parameters:

- $CR_i$: replacement cost of bridge at $i \in I$.
- $C_i$: capacity for bridge $i \in I$ before earthquakes.
- $\rho_d$: percent of remaining traffic capacity under damage state $d \in D$.
- $\rho_s$: percent of replacement cost when retrofitting strategy $s \in S$ is applied.
- $P_{dis}$: probability of damage state $d \in D$ occurs at bridge $i$ under retrofitting strategy $s \in S$.
- $F$: total desired throughput-traffic flow of the network.

Decision Variables:

- $x_{is} = 1$ if retrofit strategy $s$ is selected for bridge $i$; 0 otherwise.
- $f_{hj}$: traffic flow from nodes $h$ to $j$ on the network.

The objective (1) is to minimize the sum of the resilience enhancing investment (or retrofit cost) in the first term and the expected recovery cost in the second term. The retrofit decisions are made prior to an earthquake occurred and the subsequent expenses are evaluated in the aftermath of an earthquake. Constraints (2) and (3) require that the transportation network can support at least $F$ throughput traffic flows for both the source and sink nodes, respectively. Note that the throughput traffic flow $F$ depends on the intensity of seismic activities, and we have conducted a range of sensitivity analysis to understand the cost effectiveness of maintaining different levels of throughput traffic. The results will be reported in subsection 5.2. Constraint (4) is a flow-conservation constraint, meaning that the traffic flows into node $k$ should be equal to the flow out of the node. Constraint (5) states that the traffic on path $(h, j)$ is limited to the minimum capacity of bridges on that path. The equality (6) states that each bridge can only receive only one retrofit strategy, including the option of “do nothing”. Constraints (7) and (8) are nonnegativity constraints on decision variables.

It is noted that although this research focuses on sending rescue resources, the model can additionally be used to model an evacuation scenario by simply reversing the traffic flows in the network.

4. CASE STUDY OF CHARLESTON AREA, SOUTH CAROLINA

4.1 Description of Charleston area

The Charleston area in South Carolina is composed of numerous towns, crossroad communities, as well as unincorporated rural areas. This allows the region to offer many options to its residents in terms of residential locations and employment opportunities. Charleston is also a critical economic hub due to the Port of Charleston being one of the largest deep-water shipping ports and freight shipping centers in the US. Regional access in the region is provided by two important interstate highways and three major US Routes which are interstate freeways I-26 and I-526 and state highways US 17, US 52, and US 78 (See Figure 1).

The main threat to Charleston’s infrastructure comes from natural disasters. From historical data, the natural disasters to be most likely to affect Charleston are severe storms, earthquakes, flooding, and tornadoes [22]. Charleston is the site of one of the strongest earthquakes to hit the eastern seaboard of the United States. The earthquake occurred in 1886 and registered with an approximate magnitude of
7 on the Richter scale [22]. The damages seen to Charleston alone were estimated to be $281 to $338 million in terms of 2012 dollars [22]. Although this event happened over 120 years ago, due to its occurrence it has been theorized it will happen again. Using the loss assessment program, HAZUS, funded and developed by FEMA (Federal Emergency Management Agency), studies have been done to model 1886 Charleston earthquake if it were to happen again. Economic loss from the Charleston region would be over $14 billion, and many bridges would be damaged to the point they would no longer be usable cutting off portions of Charleston only accessible by bridges [23]. Thus, it is clear that retrofitting bridges in the Charleston area is critical for maintaining the functionality of bridges itself but also critical for supporting traffic maneuvers in emergency scenarios such as post-earthquake rescue resource dispatching or evacuation. In particular, this research effort aims to provide timely and sufficient aid to downtown Charleston in an event of earthquake.

According to the National Bridge Inventory (NBI) there are 281 bridges within the Charleston area that are annually accessed [24] and this number does not include bridges being constructed or having major reconstruction within the last 10 years. Of the 281 bridges, it was found that 36 are structurally deficient and 62 bridges are functionally obsolete. Of the bridges located within the Charleston region 38% of the bridges are deficient, which is significantly higher than the national average of one in four bridges (25%) being deficient [24]. According to FHWA, bridges are considered
structurally deficient if significant load carrying elements are found to be in poor condition due to deterioration and/or damage, or the adequacy of the waterway opening provided by the bridge is determined to be extremely insufficient to the point of causing overtopping with intolerable traffic interruptions. Bridges are considered functionally obsolete when the deck geometry, load carrying capacity (comparison of the original design load to the current state legal load), clearance, or approach roadway alignment no longer meet the usual criteria for the system of which it is an integral part [25]. In this study, using the NBI data for the state of South Carolina provided to the HAZUS program, we first filter bridges by counties to limit the case study to the area of interest in Charleston area and then select the bridges that fell along the major highways (i.e., interstate freeways I-26 and I-526 and state highways US 17, US 52, and US 78). Within these selected bridges, only those with traffic volumes above the Annual Average Daily (AADT) of 5000 veh/day were considered to be significant and included in the study. An inventory of 79 bridges was finally selected and marked in Figure 1.

4.2 A Generation of a Diagram for the Study of Charleston Area
We define a diagram that depicts the transportation network in Charleston for model use in Figure 2. On the network, the numbered nodes (i.e., nodes #1 to #11) represent junctions of the highways as well as source and sink nodes. In particular, four source nodes (i.e., nodes #1 to #4) were set for the external flows due to the rescue resources along the major highways as they enter the Charleston (i.e., originated along US 17

Figure 2.  Diagram of charleston transportation network for model use
West, I-26 South, US 52 South, and US 17 East) and a sink node (i.e., node #11) was set for the downtown of Charleston. The model allows for external flow from all four source nodes to be considered concurrently. The roadways containing the bridges were considered to be the links of the network. The bridges on a given path were grouped and considered to be in series. There are 12 groups of bridges, denoted as E, Q, C, K, G, J, H, N, P, L, O, and M in Figure 2. Each group may contain various numbers of bridges and we assumed that all bridges are independent from each other, meaning that damage to one bridge would not affect the others. The traffic flow that can traverse a path is limited to the bottleneck of that path, i.e., the bridge with lowest capacity. This aggregation greatly simplifies the model formulation and solution. Rather than treating 79 bridges individually, the index $i$ in the model now refers to as the bridge groups.

In this study, only links (6, 7) and (9, 10) are bi-directional while others can only be used for flow into downtown Charleston. These links were chosen as bi-directional because they are connector segments that would not truly cause the traffic to be pushed further back in the network but allowed it to cross to another link.

### 4.3 Structural and Earthquake Related Data Description

As determined in [26] according to the recommendations by the SCDOT (South Carolina Department of Transportation), earthquakes of magnitude ($M_W$) 5.5 and 7.0 located at $32.9^\circ$ N, $80.0^\circ$ W were selected to evaluate the highway network in this study. The traffic capacities for the 79 bridges were estimated using the Highway Capacity Manual (HCM) Procedures for Estimating Highway Capacity [27] with the bridge dimensions provided from the HAZUS program.

The HAZUS uses geographic information system (GIS) technology to estimate physical, economic, and social impacts of disasters. The seismic fragility curves and bridge classification data, located within HAZUS, are based on the NBI data. This classification scheme incorporates various parameters that affect damage into fragility analysis and provides a means to obtain fragility curves that are bridge type specific, allowing the probability of each damage state to be found and used within the model. A total of 28 classes are defined this way helping differentiate between the different bridge characteristics found in the NBI. With the latitudes and longitudes of the bridges, the HAZUS software was used to evaluate the aforementioned earthquake event and determine its impacts on the bridge network in terms of the probability ($P_{dis}$) of each damage state and the replacement cost ($CR_i$) for each bridge.

The probabilities adopted from HAZUS program represent the “do nothing” (S0) retrofit alternative. These probabilities were then modified to represent the probabilities of each damage state when a retrofit strategy other than “do-nothing” is applied, i.e., $S_1$, $S_2$, $S_3$, and $S_4$. In this research, it is assumed 10%, 15%, 20%, and 25% reductions in the risk if a bridge respectively takes retrofit strategies $S_1$, $S_2$, $S_3$, and $S_4$ and thus the corresponding probabilities are 90%, 85%, 80%, and 75% of their respective probabilities of strategy S0, i.e., $P_{d,i,0} = 90\% \ P_{d,i,0}$, $P_{d,i,1} = 85\% \ P_{d,i,0}$, $P_{d,i,2} = 80\% \ P_{d,i,0}$, and $P_{d,i,3} = 75\% \ P_{d,i,0}$, $d \in D, i \in I$. Note for each strategy, as aforementioned, the summation of probabilities over the five damage states (i.e., d0-d4) equals one.
The probability of no damage (i.e., $d_0$) increases with higher retrofit strategies while the probabilities of the other damage states decrease.

The estimate of actual cost of retrofitting bridges is challenging as very few states have completed extensive retrofit programs, from which to take data. The FHWA has complied data based on California Department of Transportation experience in retrofitting 165 bridges during 1993 and 1994 in Table 1. The costs are expressed as percentages of new construction or replacement for same time frame and the low, average, and high ranges of estimates are provided. In this research, the “average” retrofit cost range is used due to South Carolina’s lower seismic risk when compared to California. We have also considered both low and high ranges as sensitivity analysis and report the results in the case study results section 5.2. The cost of strategy S0 is zero and the strategy S4 costs as much as the new construction of a bridge. An enhanced strategy normally costs more. For example, when the superstructure is retrofitted (corresponding to the retrofit strategy S1 in this study) the average cost is 3.1% of new construction cost. When the substructure is also considered along with the superstructure (i.e., strategy S2) the average cost increases to 15.4 percent. Finally, when the foundation, super, and substructures (i.e., strategy S3) are all included the average price increases further to 28.8 percent. The new replacement cost for each of the bridges was adopted from HAZUS, ranging widely between $0.1m and $127m, which is relevant to their geographic locations and bridge types. The retrofit cost could then be estimated by multiplying the cost with corresponding percentages $\eta$. For example, when the strategy S1 is applied, the retrofit cost is estimated at $CR_i \times 3.1\%$.

5. CASE STUDY RESULTS

The optimization model was programed using AMPL [28] and solved by the commercial optimization solver CPLEX12.4.

5.1 Baseline Case

A baseline case refers to the scenario before any retrofit strategy is applied to bridges, i.e., strategy “do nothing” (S0) applied to all bridges. The baseline case was established for the potential damages associated with both the $M_w$ 5.5 and $M_w$ 7.0 events. Having
the baseline will first allow for the results from the model to be compared in terms of total system cost and validate the retrofitting strategies chosen by the model. Secondly, it demonstrates the need for retrofitting if the chosen earthquake events were to happen and the benefits that can be achieved. Finally, it provides the worst-case scenario of throughput traffic capacity that the network can support.

Using the results from the HAZUS program (Table 2) it was found that for the $M_W$ 5.5 event 40% of the bridges in the study area will receive slight, moderate, extensive, or complete damage and the expected damage cost is approximately $142 million with an expected throughput traffic capacity of 14,377 veh/hr. For the $M_W$ 7.0 event, 42% of the bridges would be receiving slight, moderate, or extensive damages, while 40% of bridges are expected to fail completely and the expected damage cost is approximately $369 million with an expected throughput traffic capacity of 2,411 veh/hr. Please note that the throughput traffic capacity is a combined effect of all bridges on the network as well as the network structure. In this case, the traffic capacity is a summed traffic flows entering the network to downtown Charleston via the four source nodes (i.e., nodes #1 - #4 in Figure 2). The baseline analysis also implies that in the case the Charleston earthquake of 1886 (registered with an approximate $M_w$ 7.0) was to be repeated, 82% of the bridges in the area would be damaged if no retrofitting was put in place.

### Table 2. Baselines of potential damage to the charleston area

<table>
<thead>
<tr>
<th>Damage States</th>
<th>Percent of Bridges (%) affected in earthquake events</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$M_W$ 5.5</td>
</tr>
<tr>
<td>none</td>
<td>60</td>
</tr>
<tr>
<td>Slight</td>
<td>12</td>
</tr>
<tr>
<td>Moderate</td>
<td>8</td>
</tr>
<tr>
<td>Extensive</td>
<td>11</td>
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<tr>
<td>Complete</td>
<td>9</td>
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</tbody>
</table>

5.2 Numerical Solutions of Retrofit Optimization Program and Analysis

We first use the model (1)-(8) to identify the expected maximum throughput traffic capacity, which is obtained by treating $F$ as a variable in the model and maximizing it without any budget constraint. The maximum traffic capacities the network is capable of handling for the $M_W$ 5.5 and $M_W$ 7.0 events were found to be 20,841 veh/hr and 11,828 veh/hr, respectively. With the lower bound of traffic capacity obtained from the baseline case, we assume six different traffic capacity levels to create a full spectrum of desired flows of sending rescue resources into the downtown Charleston in the case of extreme events. In particular, they are throughput traffic capitates of 14,377, 15,000, 16,500, 18,000, 19,500 and 20,841 veh/hr for the $M_W$ 5.5 event, and traffic capitates of 2,411, 4,000, 6,000, 8,000, 10,000 and 11,828 veh/hr for the $M_W$ 7.0 event.
Table 3. Optimal retrofit strategies and associated costs for various traffic capacity levels for $M_W$ 5.5 event

<table>
<thead>
<tr>
<th>Desired Throughput (Veh/Hr)</th>
<th>Retrofit cost ($m)</th>
<th>Expected damage cost ($m)</th>
<th>Total Cost ($m)</th>
<th>Retrofit Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>14,377</td>
<td>3.59</td>
<td>134.82</td>
<td>138.41</td>
<td>S0</td>
</tr>
<tr>
<td>15,000</td>
<td>3.59</td>
<td>134.82</td>
<td>138.41</td>
<td>S1</td>
</tr>
<tr>
<td>16,500</td>
<td>3.59</td>
<td>134.82</td>
<td>138.41</td>
<td>S2</td>
</tr>
<tr>
<td>18,000</td>
<td>4.19</td>
<td>134.69</td>
<td>138.88</td>
<td>S3</td>
</tr>
<tr>
<td>19,500</td>
<td>7.14</td>
<td>134.04</td>
<td>141.18</td>
<td>S4</td>
</tr>
<tr>
<td>20,841</td>
<td>20.52</td>
<td>132.50</td>
<td>153.03</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Optimal retrofit strategies and associated costs for various traffic capacity levels for $M_W$ 7.0 event

<table>
<thead>
<tr>
<th>Desired Throughput (Veh/Hr)</th>
<th>Retrofit cost ($m)</th>
<th>Expected damage cost ($m)</th>
<th>Total Cost ($m)</th>
<th>Retrofit Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,411</td>
<td>16.73</td>
<td>332.23</td>
<td>348.96</td>
<td>S0</td>
</tr>
<tr>
<td>4,000</td>
<td>16.73</td>
<td>332.23</td>
<td>348.96</td>
<td>S1</td>
</tr>
<tr>
<td>6,000</td>
<td>16.73</td>
<td>332.23</td>
<td>348.96</td>
<td>S2</td>
</tr>
<tr>
<td>8,000</td>
<td>17.86</td>
<td>331.84</td>
<td>349.70</td>
<td>S3</td>
</tr>
<tr>
<td>10,000</td>
<td>23.18</td>
<td>330.37</td>
<td>353.55</td>
<td>S4</td>
</tr>
<tr>
<td>11,828</td>
<td>55.99</td>
<td>324.75</td>
<td>380.73</td>
<td></td>
</tr>
</tbody>
</table>
The chosen traffic throughput levels were different for each event due to the differing levels of expected damage the network was to receive. The $M_W$ 5.5 event will have less damage to the bridges within the network, and the traffic throughput levels chosen for the $M_W$ 7.0 event may not be significant when applied. The chosen throughput levels ensure the model demonstrates its ability to mitigate damage while meeting the throughput at a variety of levels. The model was ran separately for each of the six traffic capacity levels and the resulting retrofitting costs, expected damage costs, total cost, and number of bridges receiving different strategies are displayed in Tables 3 and 4 for $M_W$ 5.5 and $M_W$ 7.0 earthquake events, respectively. Please note that the solution set is based on the average range of cost of retrofit strategies in Table 1 and it is referred to herein as solutions ($P_{5.5}$ and $P_{7.0}$ for $M_W$ 5.5 and $M_W$ 7.0 events).

The results from Tables 3 and 4 indicate that although retrofit cost is minimal compared to the damage cost, optimized retrofit strategy sets can make the network more cost effective and greatly improve the network traffic capacity. For example, for the $M_W$ 5.5 event, a retrofit strategy set (i.e., 34 receiving no retrofit and 45 bridges receiving S1 strategy) with a total retrofit cost of $3.59m can help reduce the expected damage cost by 5% ($=(135–142)/142$) or 2% ($=(138–142)/142$) overall cost reduction (including both retrofit and damage costs) for supporting traffic capacity of 14,377 veh/hr. For the $M_W$ 7.0 event the economic effectiveness is more substantial. Because of the retrofits, the

Figure 3. Bridge retrofit strategies for $M_w$ 5.5 event
overall network traffic capacity has been significantly improved. For instance, for the M\textsubscript{w} 5.5 event, the throughput traffic capacity is gone up by 45% \((=(20,841 – 14,377)/14377)\) with a cost increase of only $15m = ($153–138m). For the M\textsubscript{w} 7.0 event, the network capacity has been increased fourfold with a cost of only $32m.

The decision making on optimal retrofit decisions is complex, which is the result of combined effects of traffic capacity levels, the earthquake intensities, structural conditions, and the transportation network. In general, a higher traffic capacity or higher earthquake intensity requires more enhanced strategy set as indicated in Tables 3 and 4. The resultant retrofit strategies for the M\textsubscript{w} 5.5 and M\textsubscript{w} 7.0 events are also mapped in Figures 3 and 4 respectively for each of the 79 bridges when the largest traffic capacities (i.e., 20,841veh/hr for the event of M\textsubscript{w} 5.5 and 11,828 for the event of M\textsubscript{w} 7.0) are considered. In both figures, darker color denotes a more enhanced (higher numbered) retrofit strategy applied. In both cases, bridges on highways I-26 and US 78 received more enhanced retrofit strategies than other routes, mainly because these two highways carry more traffic flows than the others.

In this study, the effects of a critical parameter, retrofit cost, expressed in terms of percentage of new construction costs \(\eta\), were further evaluated on the strategy for both the M\textsubscript{w} 5.5 and M\textsubscript{w} 7.0 events by using the “low” and “high” ranges from Table 1. The optimization model was re-run for these two ranges and the results are plotted in Figures 3 and 4. From the results, it is easy to see the benefits of adopting retrofit strategies when comparing to if no retrofitting was done. In both cases, for the same level of traffic capacity, optimized retrofitting reduces the overall cost and enables increase of network traffic capacity. The total retrofit and damage costs may vary.
Figure 5. $M_w$ 5.5 Solution comparison

Figure 6. $M_w$ 7.0 Solution comparison
significantly with different retrofit cost ranges used. For example, for the $M_{w}$ 5.5 event, an overall cost difference when comparing high and cost retrofit cost ranges is between $19m and $30m and this cost difference is more substantial ranging between $61 and $87m for the $M_{w}$ 7.0 event.

The retrofit strategies are presented in Table 5. It shows that for the “low” retrofit cost range, as it lowers the weight on the retrofit cost in the objective, selecting enhanced (higher numbered) strategies can help reduce the expected damage cost and the total cost. The “high” retrofit cost range on the other hand makes it more economical to choose strategies that merely meet the traffic capacity requirement.

### Table 5. Retrofit strategies for “Low” and “High” retrofit cost ranges

<table>
<thead>
<tr>
<th>Events Throughput (Veh/Hr)</th>
<th>Desired Retrofit Strategies</th>
<th>Low retrofit cost range</th>
<th>High retrofit cost range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{w}$ 5.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14,377</td>
<td>0 0 34 45 0</td>
<td>79 0 0 0 0</td>
<td></td>
</tr>
<tr>
<td>15,000</td>
<td>0 0 34 45 0</td>
<td>78 1 0 0 0</td>
<td></td>
</tr>
<tr>
<td>16,500</td>
<td>0 0 34 45 0</td>
<td>73 6 0 0 0</td>
<td></td>
</tr>
<tr>
<td>18,000</td>
<td>0 0 34 45 0</td>
<td>71 6 1 0 1</td>
<td></td>
</tr>
<tr>
<td>19,500</td>
<td>0 0 34 45 0</td>
<td>63 11 1 0 4</td>
<td></td>
</tr>
<tr>
<td>20,841</td>
<td>0 0 34 38 7</td>
<td>57 4 4 0 14</td>
<td></td>
</tr>
<tr>
<td>$M_{w}$ 7.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,411</td>
<td>0 0 0 79 0</td>
<td>79 0 0 0 0</td>
<td></td>
</tr>
<tr>
<td>4,000</td>
<td>0 0 0 79 0</td>
<td>76 3 0 0 0</td>
<td></td>
</tr>
<tr>
<td>6,000</td>
<td>0 0 0 79 0</td>
<td>60 18 1 0 0</td>
<td></td>
</tr>
<tr>
<td>8,000</td>
<td>0 0 0 79 0</td>
<td>56 18 3 0 2</td>
<td></td>
</tr>
<tr>
<td>10,000</td>
<td>0 0 0 78 1</td>
<td>53 13 3 0 10</td>
<td></td>
</tr>
<tr>
<td>11,828</td>
<td>0 0 0 60 19</td>
<td>53 2 1 0 23</td>
<td></td>
</tr>
</tbody>
</table>

The retrofit strategies are presented in Table 5. It shows that for the “low” retrofit cost range, as it lowers the weight on the retrofit cost in the objective, selecting enhanced (higher numbered) strategies can help reduce the expected damage cost and the total cost. The “high” retrofit cost range on the other hand makes it more economical to choose strategies that merely meet the traffic capacity requirement.

### 6. CONCLUSIONS

In this study, we developed an optimal modeling framework to determine best retrofit strategies for a network of highway bridges. It aims to achieve the least total cost of retrofitting and the subsequent damage while satisfying the traffic capacity of the network. The model explicitly integrates the effects of the traffic network and the bridge seismic assessment of damage states into the retrofit decision making scheme.

The model was implemented on an empirical Charleston case study. The results indicate that decisions on retrofit strategy are highly dependent on traffic capacity requirement and related to the network topology. They also justify the importance of integrating the traffic network into the decision making process and including both the retrofit and sequent damage costs in the objective. For a given retrofit price range (e.g.,
low, average, or high), increased traffic throughputs require higher or more enhanced retrofitting strategies. For the “low” retrofit cost range, as a lower weight is placed on the retrofit cost in the objective, enhanced (or higher numbered) strategies would be chosen to reduce the expected damage cost and the system cost. This occurs due to the retrofit benefits to the expected damage outweighing the cost of retrofitting. Adversely, for the “high” retrofit cost range, as a greater weight is placed on the retrofit cost in the objective, strategies that merely meet the traffic throughput requirement of the network would be chosen. This is due to the cost of retrofitting outweighing the reduction to the expected damage of the network. For the “average” retrofit cost range, a balance was seen between the retrofit strategies chosen and meeting capacity. The model would choose to retrofit a majority of bridges with at least strategy S1 (Superstructure), and then only enhance the strategy on the most critical bridges to the network traffic capacity. This allowed the network to meet the desired traffic throughput and mitigate expected damages on a majority of bridges.

While this work has demonstrated the potential for using modeling to determine retrofitting strategies at minimum costs, many opportunities for extending the scope of this study remain. Future research can be accomplished to further this study through the incorporation of a greater number of direct damages, or costs into the objective, the incorporation of all possible hazards (earthquake, wind, and flood) to a region, and research into true retrofit costs.

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