MPC-675
November 12, 2021

Project Title

Transition of Allowable Stress Rating to Load and Resistance Factor Rating for Timber Bridges

University

University of Colorado Denver

Principal Investigators

Jimmy Kim
Professor
University of Colorado Denver
Phone: (303) 315-7497
Email: jimmy.kim@ucdenver.edu
ORCID: 0000-0002-4286-1461

Research Needs

All bridges in the United States are inspected every two years and, pursuant to the Code of Federal Regulations (Title 23, Part 650, Subpart C, 650.303(c)), both new and existing bridges are subjected to load rating. The purpose of ratings is to identify a load level that a bridge can accommodate without excessive distress, which is an important task to effectively control the safety of constructed bridges. The item numbers of 58 through 60 in the National Bridge Inventory (NBI) are concerned with condition states: deck (Item 58), superstructure (Item 59), and substructure (Item 60). Regarding rating outcomes, Items 63 and 64 are about the determination of Operating Rating and rating values in metric tons, respectively, and Items 65 and 66 indicate the determination of Inventory Rating and rating values in metric tons, respectively. The Operating Rating level is related to the maximum permissible live load of a highway bridge; by contrast, the Inventory Rating level is intended to reflect stresses belonging to customary bridge design and provides a live load that can be allowed for an indefinite time period.

The Federal Highway Administration (FHWA) has mandated the Load and Resistance Factor Design (LRFD) method since 2007 (FHWA 2000); accordingly, although not necessarily part of these requirements, bridge appraisals should be aligned with Load and Resistance Factor Rating (LRFR) for consistency. However, traditional Allowable Stress Rating (ASR) is frequently adopted for timber bridges because the majority of them were constructed in accordance with the Allowable Stress Design (ASD) method.

The AASHTO Manual for Bridge Evaluation (AASHTO 2017) allows both ASR and LRFR for timber bridges, while its implementation varies across the nation. States such as Colorado, Connecticut, Minnesota, and Washington enforce the use of ASR (CTDOT 2018; MnDOT 2018; WSDOT 2020; CDOT 2021); on the other hand, LRFR is adopted by some states (e.g., Arizona, Iowa, and Florida) and some states do not employ ASR (e.g., Delaware and Nevada). Such a trend in acceptable rating methods signifies that there are transitional endeavors from ASR to LRFR when dealing with timber bridges, which is analogous when AASHTO LRFD Bridge Design Specifications replaced the AASHTO Standard Specifications decades ago.

One of the critical challenges facing the infrastructure community is that transportation agencies do not have sufficient information whether ASR provides a better rating for timber bridges compared with LRFR or vice versa. In other words, simple analytical calculations will merely generate rating factors without knowing the actual performance of timber bridges. Refined investigations are, thus, necessary for addressing this practical matter in order to advance the state of the art of bridge rating technologies. The proposal discusses a comprehensive research program to elucidate the applicability of ASR and LRFR in timber bridges and aims to suggest an appropriate rating protocol. In so doing, bridge owners can properly manage built-environments and efficiently spend funds on maintenance and traffic control.

Research Objectives

The overarching goals of the research are:

- To understand the level of conservatism and applicability of ASR and LRFR in the performance evaluation of timber bridges, based on three-dimensional finite element analysis
- To appraise design factors associated with LRFR against the ultimate state of timber bridges and, if necessary, suggest new factors to better reflect the condition state of those bridges using reliability theory
- To understand the mechanical response of timber elements subjected to flexural loading
- To examine the efficacy of various retrofit systems that are used to upgrade deteriorated timber bridge members
- To evaluate rating methodologies against the findings of the experimental program with and without the retrofit systems
- To develop practice recommendations, which can assist in replacing ASR with LRFR for timber bridges

Research Methods

It is important to appropriately diagnose the condition of bridge members, so that rating factors can represent realistic live load effects. Given that destructive testing is unlikely on most occasions, finite element models will be developed. Among the three rating methodologies used in practice, the ASR and LRFR methods will be of interest in this study. The ASR approach (Eq. 1) is based on the principle of working stress; on the other hand, the LRFR method (Eq. 2) is related to the concept of structural reliability (AASHTO 2017):

$$RF = \frac{C - D}{L(1+I)} \tag{1}$$

$$RF = \frac{C - \gamma_{DC} DC - \gamma_{DW} DW \pm \gamma_p P}{\gamma_{LL}(L + IM)} \tag{2}$$

where RF is the rating factor; C is the load-carrying capacity of the member (allowable capacity in ASR); D and L are the dead and live load effects, respectively; DC, DW, and P are the structural components, wearing surface, and other permanent loads, respectively; I is the impact factor; IM is the dynamic load allowance; and γ_{DC}, γ_{DW}, γ_P, and γ_{LL} are the load factors for the structural components, wearing surface, permanent loads, and live load, respectively. The design rating of ASR is based on HS20-44 (8 kips + 32 kips + 32 kips), while that of LRFR involves HL-93 (8 kips + 32 kips + 32 kips plus 0.64 kips/ft) and tandem (25 kips + 25 kips plus 0.64 kips/ft). For timber bridges with ASR, the Inventory stress equals the allowable stress and the Operating stress is 1.33 times the allowable stress (AASHTO 2017). In addition, the unique short-term response of timber does not necessitate the impact and dynamic load allowance terms when rated ($I = IM = 0$); that is, the instantaneously increasing load-carrying ability of a timber bridge can offset the ramifications of dynamic amplification. Complying with the AASHTO Manual for Bridge Evaluation (AASHTO 2017), two rating categories will be considered: Inventory and Operating levels. The implications of several aspects belonging to ASR and LRFR will be documented; for example, vehicle loadings, live load distributions, and calibration factors. A proof load test, which is often conducted with a known-weight truck equivalent to the Operating level of live load effects, will be part of the planned research: the Colorado Department of Transportation (CDOT) provides the response data of a timber bridge situated in the Denver metropolitan area.

These rating approaches will be assessed using laboratory test data. The Colorado Department of Transportation will supply timber girders salvaged from a decommissioned bridge. These girders will be transported to the laboratory at the University of Colorado Denver and prepared for testing. The behavior of the girders with and without retrofit will be examined and technical findings will be used to assist the development of the aforementioned ASR and LRFR methods. Comprehensive outcomes are expected to handle both unstrengthened and strengthened timber bridges.

Expected Outcomes

Despite the fact that ASR is deemed obsolete, some DOTs still utilize it under certain circumstances (e.g., timber and masonry bridges). For instance, the Bridge Rating Manual of Colorado states that all timber bridges shall be rated per ASR without impact (CDOT 2021). Such a conventional approach may yield reasonable ratings, whereas the actual response of a bridge structure is largely unknown owing to the overly simplified ASR method. Furthermore, insufficient guidance is available on the implementation of LRFR for timber bridges. The research will clarify the technical appropriateness of ASR through three-dimensional finite element analysis and will establish the foundation of selecting the right rating method for timber bridges. The newly added components of laboratory testing will clarify the appraisal of the modeling task and will add benefits in terms of establishing a relationship between rating and retrofit.

Relevance to Strategic Goals

The proposed research will be relevant to the Secretary of Transportation's Strategic Goals: *State of Good Repair* and *Economic Competitiveness*. Upon successful completion of technical tasks, transportation authorities will adequately assess the state of existing timber bridges, which will be linked with finding proper repair methods at affordable expense.

Educational Benefits

Senior and graduate students taking the PI's infrastructure course (CVEN5800 *Infrastructure Rehabilitation*) will directly benefit from this research. The course is composed of three major contents: i) Properties of Materials, ii) Evaluation of Existing Structures, and iii) Rehabilitation Methods. Unlike the first and third contents, the second part is relatively undervalued due to a lack of cutting-edge research in the area of bridge ratings. The primary reason is that most researchers and practitioners merely follow the methodologies specified in the AASHTO Manual for Bridge Evaluation (AASHTO 2017) and state DOT rating manuals; consequently, subjects outside routine practices are not well studied. The outcomes of the planned research will be a valuable source to broaden the technical insights of next generation workforce.

Technology Transfer

Research findings will be shared with government officials, practitioners, and engineering students. Technical contents will be published in renowned journals and conference proceedings. The PI will attempt to disseminate the state-of-the-art knowledge in professional committee meetings and workshops.

Work Plan

Task 1: Literature review (Months 1 to 3)

Published documents will be collected to understand the state of the art of bridge ratings. Because many technical reports, research papers, and practice manuals are concerned with ASR for timber bridges, a literature search will be conducted with a focus on comparative assessments between ASR and LRFR for other bridge types (e.g., concrete and steel girders). In so doing, the pros and cons of these rating methods will be identified and corresponding outcomes will assist in planning subsequent tasks. Additionally, the state of the art of testing timber girders and retrofit schemes for deteriorated members will be reviewed. Conventional and emerging technologies will be of interest such as lag bolting, supplementary steel elements, and carbon fiber reinforced polymer.

Task 2: Experimental program (Months 4 to 7)

Salvaged timber girder will be acquired from the Colorado Department of Transportation and will be transported to the laboratory at the University of Colorado Denver. Flexural testing will be conducted with and without retrofit. Data will be collected and analyzed to examine the effectiveness of the strengthening approaches, which will be crucial for developing rating methodologies.

Task 3: Assessment of rating methods against test data (Months 7 to 10)

The experimental results from Task 2 will be employed to appraise the modeling work that has been delineated in the initial proposal. The integrated findings will form the basis of refining ASR and LRFR to best identify the applicability of these rating approaches for strengthened and unstrengthened timber bridges.

Task 4: Finite element modeling (Months 11 to 16)

The benchmark bridge to be modeled will be F-22-V in Colorado. This three-span bridge (L = 21.5 m (70 ft)) was built in 1938 to accommodate two traffic lanes and the design load was H15. An average daily traffic of 690 vehicles was measured in 2018. According to the National Bridge Inventory (NBI) in 2020, the condition ratings of the bridge were 6 for the deck, 4 for the superstructure, and 6 for the substructure. As far as load ratings are concerned, Inventory and Operating Ratings of 17.2 tons and 30.8 tons were assigned and no posting was necessary. In 2021, the bridge was repaired with three methods by the Colorado Department of Transportation (CDOT): sister steel beams, lag bolting, and carbon fiber reinforced polymer (CFRP) sheets. The behavior of the bridge will be predicted using finite element software, which will be validated against load test data measured in the field.

Task 5: Parametric investigations (Months 17 to 18)

The validated modeling technique will be employed to carry out a parametric study. Variables include timber species, size of stringers, traffic lanes, loading types (HS-20, Colorado Legal trucks, Interstate Legal trucks, Specialized Hauling Vehicles, Emergency Vehicles, and Colorado Permit trucks), damage levels, and repair methods. The degree of adequacy in ASR and LRFR will be quantified to recommend a possible transition.

Task 6: Extension to full-scale bridge models (Months 19 to 20)

Multiple full-scale timber bridges will be modeled and the best performing retrofit scheme will be included to comparatively investigate the rating methodologies. A wide variety of bridge responses will be investigated (e.g., stress levels, deflections, and live load distributions).

Task 7: Assessment of rating methods (Months 21 to 22)

The predicted data to be provided from Task 3 will be utilized to evaluate the rating methodologies. Following present practice, ASR will first be determined for both Inventory and Operating levels; afterward, LRFR will be calculated. If necessary, empirical rating coefficients will be recalibrated as per reliability theory and new rating equations will be proposed to adequately rate timber bridges. The probability of failure will be enumerated as a metric for safety.

Task 8: Final report (Months 23 to 24)

A final report will be submitted before the end of a contract date.

Project Cost

Total Project Costs:	$160,000
MPC Funds Requested:	$ 80,000
Matching Funds:	$ 80,000
Source of Matching Funds:	Colorado Department of Transportation, financial support, in-kind support, and facilities

References

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