# VIRTUAL Workshop on Redundancy in Bridges for Risk Mitigation in a Multi-Hazard Environment

## July 21, 2020 (10 AM to 4:00 PM EST)

## July 28, 2020 (10 AM to 3:50 PM EST)

## Organized by

Dr. Anil K. Agrawal (The City College of New York)

Dr. Sherif El-Tawil (University of Michigan)

Dr. Baidurya Bhattacharya (IIT Kharagpur, India)

Dr. Hani Nassif (Rutgers University)

## Sponsored by

Federal Highway Administration (FHWA)

## FHWA Contact

Mr. Waider Wong

# Bridge redundancy as a hazard mitigation tool?

Recent collapse of several bridges, such as the I-35 truss bridge in Minneapolis in 2007, Ponte Morandi cable stayed bridge in Genoa, Italy, in 2018, Florida International University Pedestrian Bridge in 2018 and Nanfang'ao steel single-arch bridge in Taiwan in 2019, have highlighted the importance of the role of redundancy in the safety of bridges. The purpose of this virtual workshop is to identify needs and gaps in the current state-of-the-art / practice on different aspects of redundancy, which is defined as “the quality of a bridge that enables it to perform its design function in the damaged state”. The commentary of the AASHTO LRFD Bridge Design Specification (C.1.3.2.1) notes that the current approach of incorporating redundancy in bridge design is “arbitrary” and "subjective”. The use of redundancy as a means for hazard mitigation in the event of loss of a critical member has also not been explored in the current framework. Current simulation technology has advanced to the point where it can be used for assessing the effect of member criticality on the overall system collapse response. This approach is more rational and objective for assessing redundancy in critical and important bridges, but particularly for long-span bridges which are critical assets. There is therefore an urgent need for an open forum discussion through a workshop for assessing the current framework on redundancy and identifying the gaps and challenges, and future research priorities.

# Workshop Program

## Presentation Sessions:

### July 21, 2020, 10:00 AM - 4:00 PM EST

https://connectdot.connectsolutions.com/sr500xbrdgewrkshp/

## Presentation Sessions

### July 28, 2020, 10:00 AM – 1:30 PM EST

https://connectdot.connectsolutions.com/sr500apanel/

**Asynchronous Session:**

**To be Decided (Electronic Discussion Board)**

https://www.linkedin.com/in/bridge-redundancy-workshop-2065461b2/

## AASHTO Sessions

### July 23, 2020 (only for AASHTO Members)

Meeting Link: TBD

## Breakout Sessions

### July 28, 2020 (2:00 PM – 3:50 PM EST)

Meeting Link: TBD

# ABSTRACTS

## Improving the Quantification of Redundancy Factor Modifiers in AASHTO LRFD Bridge Design Specifications

**JULY 21, 2020. 10:30 AM – 11:10 AM**

**Dan M. Frangopol**
The Fazlur Rahman Khan Endowed Chair of Structural Engineering and Architecture
Professor of Civil Engineering, Department of Civil and Environmental Engineering,
ATLSS Center, Lehigh University, Bethlehem, PA 18015-4729, USA

A new definition of redundancy factor to provide an improved quantification of system redundancy levels in component design is proposed. Examples are presented to illustrate this definition. The approach proposed provides the missing link between member-level reliability and system-level reliability and can be used for improving the quantification of redundancy factor modifiers in the AASHTO LRFD Bridge Design Specifications. Focus is placed on strength limit sates. In order to improve the reliability of series systems to avoid under capacity design and to reduce the reliability of parallel systems to avoid over capacity design, modifier factors that relate to redundancy by taking into account the effects of system arrangement, component behavior, correlations among the resistances of components, number of components in a system, coefficients of variation of load and resistances, and mean value of the load on the redundancy factor are investigated by using large idealized systems.

Dr. Dan Frangopol is the inaugural holder of the Fazlur R. Khan Endowed Chair of Structural Engineering and Architecture at Lehigh University. His main research interests are in the development and application of probabilistic concepts and methods to civil and marine engineering. Dr. Frangopol is the recipient of several awards from ASCE, IABSE, IASSAR, and other professional organizations, such as the Newmark, T.Y. Lin, Housner, Freudenthal, Khan and Cross Medals, and the Lifetime Achievement Award in Education (OPAL), to name a few.

**Strategies to Enhance Redundancy in Long Span Bridges: A Designer's Perspective**

**JULY 21, 2020. 11:10 AM – 11:30 AM**

**Ted Zoli**
National Chief Bridge Engineer, HNTB, New York, NY, USA

This presentation considers redundancy and robustness for long span bridges, both for new design and for inspection/rehabilitation of existing bridges. Brief examples will include all long span bridge forms (trusses, arches, cable stayed and suspension bridges). A discussion of durability, inspect ability, repairability, and replaceability, which are too often neglected in the context of redundancy will be an explored. The presentation will focus attention on design basis and in-service performance of connections. The presentation will also touch upon performance-based design and risk-based inspection as it relates to long span bridge redundancy & robustness.

Zoli serves as HNTB's National Chief Bridge Engineer and has led the design of many unique long span cable stayed, arch, and truss bridges throughout the United States. His introduction of the network arch as a form with enhanced redundancy and robustness with the Blennerhassett Island and Lake Champlain bridges has changed the way we think about arch bridges. He has introduced new concepts to truss design with the Portsmouth Memorial Bridge, where gusset plates have been eliminated, and the connections moved away from the nodal regions to enhance performance and redundancy. Zoli also serves as an adjunct professor at Columbia University where he teaches a class on long span bridge design and Notre Dame University, where his research is focused on rapidly deployable structural systems.

## Current Practices for Addressing Redundancy in the Design of Long Span Bridges

**JULY 21, 2020. 11:30 AM – 11:50 AM**

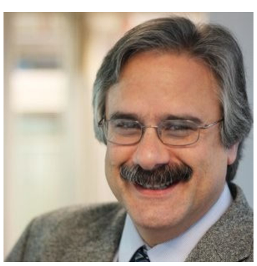
**Wagdy Wassef**
Engineering Director, WSP, New York, NY, USA

**Joseph Viola**

Complex Bridge Manager, WSP, New York, NY, USA

Generally, design specifications are often not written to consider long span bridges, admittedly a limited population of bridges designed. As a result, many gaps exist in the design specifications when it comes to the design of complex, long span bridges. Designers rely on engineering judgement, past experience and refined analysis in developing the approach used in design to achieve and verify the redundancy of bridge structures. Bridge design specifications include provisions to address redundancy, however, these provisions are not comprehensive and simply provides incentives to encourage redundant designs without detailed guidance on how to achieve redundancy or the degree of redundancy required. Project-specific criteria are often relied upon to provide direction. This presentation covers the redundancy provisions in AASHTO LRFD and a practitioner's perspective on how redundancy is achieved in the design of long span bridges.

Wagdy Wassef is an Engineering Director with WSP. He has over three decades of diversified experience on different aspects of bridges analysis, design, rehabilitation and research. Dr. Wassef has been active in updating AASHTO LRFD since the specifications was adopted in 1993. He authored many of the revisions to the specifications including the current wind load provisions, Section 15, sound barriers, and the revisions to the service limit state load factors for prestressed concrete.



Joseph Viola is a Complex Bridge Manager with WSP with over 35 years of new and rehabilitation design of long span bridges including over two dozen suspension bridges, cable stayed bridges and other complex structures. Representative projects include the New Tacoma Narrows Bridge (Engineer of Record), Benjamin Franklin Bridge Main Cable Dehumidification, A25 main cable-stayed bridge and the Upper Level Deck Replacement of the Verrazzano Narrows Bridge. He has authored several technical publications on these bridges and other topics.

## Analysis of Reliability-Redundancy Trade-off for Fire Resilience of Cable Bridges

**JULY 21, 2020.  11:50 AM – 12:10 PM**

**Hokyung Kim & Junho Song**
Department of Civil and Environmental Engineering, Seoul National University

As an effort to ensure the resilience of urban societies against natural and man-made hazards, Song (2017) proposed a system-reliability-perspective on resilience of structures, networks, and communities. In the proposed framework, resilience is characterized by reliability, redundancy, and recoverability of a system. It was also proposed to analyze a structure's resilience by a scatter plot of the reliability and redundancy indices, termed "R2 plot." This talk presents the concept of the R2 plot and its evaluation procedure developed for cable bridges under fire hazard. Probabilistic models are first developed to describe the fire-hazard on a target bridge. Based on the definitions of fire-induced component- and system-level failure events, the reliability and redundancy indices are computed for each failure scenario. To compute the indices efficiently, this study employs a reliability method that selects simulation points through surrogate-model-based learning. The pairs of the indices in the R2 plot visualize the fire resilience of the bridge especially in terms of reliability-redundancy trade-off. The concept and methods are demonstrated by a full-scale cable-stayed bridge in South Korea. The results confirm the applicability of the R2 plot framework to fire resilience assessment of bridge systems and provide discussions on reliability-redundancy trade-off from disaster resilience viewpoint.

Dr. Ho-Kyung Kim is the director of Korea Bridge Design and Engineering Research Center (KBRC), and currently serving as the Chair of the Korean Group for International Association of Bridge and Structural Engineering (IABSE), the Chair of the Korea Panel of International Association for Structural Control and Monitoring (IASCM), and an Executive Committee Member of International Association for Bridge Maintenance and Safety (IABMAS).

Dr. Junho Song is a professor at Seoul National University. His main research interests are in System Reliability and Optimization and is the recipient of several awards from ICOSSAR conference, the National Academy of Engineering of Korea and SNU. Dr. Song is currently the President of CERRA and the Chairman of the IFIP Working Group 7.5 on Reliability and Optimization of Structural Systems.

## Comparison of redundancy frameworks for Bridges

**JULY 21, 2020. 12:40 PM – 1:00 PM**

**Baidurya Bhatacharya**
Professor, Department of Civil Engineering, IIT Kharagpur

For bridge structures, existing approaches to measuring structural redundancy make use of load capacity ratios at a few pre-defined limit states and do not accord flexibility to the bridge owner in defining the set of initial damages and the system failure modes that are appropriate for the bridge, nor do they allow the use of available bridge-specific models and bridge-specific information on uncertainties.

We employ a newly developed reliability-based structural robustness index that is able to explicitly measure redundancy of high-reliability structures. The methodology couples high fidelity finite element push down analysis with generalized first order reliability method with continuously adaptive linearization points thereby avoiding costly Monte Carlo simulations. The robustness index is monotonic and bounded between 0 and 1 such that 0 signifies no residual capacity given the initial damage for the failure mode in question, and 1 signifies the structure to be indifferent to the initial damage. The index takes into account all uncertainties involved and can accommodate non-linearities both in the structural model and in the limit state. It is able to rank different structures in terms of their robustness for the same initial damage, and for the same structure, rank different initial damages in terms of severity and thereby identify the critically important members for remedial measures. A minimum acceptable value of the robustness index, derived from existing approaches, is also proposed. A simple bridge example is presented to highlight the difference between the existing approaches and the proposed one.

Dr. Baidurya Bhatacharya is currently a professor at the Indian Institute of Technology Kharagpur. His research interests include material degradation and probabilistic mechanics. Over the years, Bhattacharya has worked on load modelling, time-dependent reliability analysis, system reliability and progressive collapse, target reliabilities, LRFD based design and evaluation criteria, microstructural damage growth, heat conduction, damage detection and system identification problems. He has applied these variously to nuclear power plant reactors and containments, buildings, bridges, ship and offshore structures. He served as Associate Editor of the Journal of Bridge Engineering ASCE for eight years. He is a Fellow of the Indian National Academy of Engineering and a Fellow of the American Society of Civil Engineers.

## Redundancy of long-span cable supported bridges

**JULY 21, 2020. 1:00 PM – 1:20 PM**

**Sherif El-Tawil**
Antoine E. Naaman Collegiate Professor of Civil and Env. Engineering,
Dept. of Civil & Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125, USA

Redundancy is commonly defined as "the quality of a bridge that enables it to perform its design function in the damaged state". The word redundancy has a historical link to the computation of static indeterminacy and its association with alternate, hence 'redundant', load paths. This presentation will attempt to move the terminology away from 'redundancy' to 'robustness' instead, which is more descriptive of the intent of bridge designers and owners to have a structure which can "withstand or overcome adverse conditions". A newly proposed robustness index will be outlined and its advantages of dealing with long span bridges highlighted. The Cooper River Bridge, a cable stayed bridge with an unsupported span of 1546 ft (471 m), will be used as a case study to demonstrate the new technique. A well calibrated high-fidelity finite element model of the bridge will be first introduced then used to contrast between the new robustness index and an established approach. An argument will be presented in support of using the new index for measuring the robustness of long span bridges and providing a rational way for managing their repair after extreme events.

Dr. Sherif El-Tawil is Antoine E. Naaman Collegiate Professor of Civil and Environmental Engineering Department at the University of Michigan, Ann Arbor. Dr. El-Tawil's general research interest lies in computational modeling, analysis, and testing of structural materials and systems. He is especially interested in how buildings and bridges behave under the extreme loading conditions generated by manmade and natural hazards such as seismic excitation, collision by heavy objects, and blast. A Fellow of the American Society of Civil Engineers, Dr. El-Tawil is Editor-in-Chief for the Society's Journal of Structural Engineering. He is recipient of the Korean Concrete Institute's Paper of the Year Award and ASCE's State-of-the-Art Award, Huber Research Prize, Moisseiff Award (twice), Wellington Prize, Torrens Award, and Norman Medal.

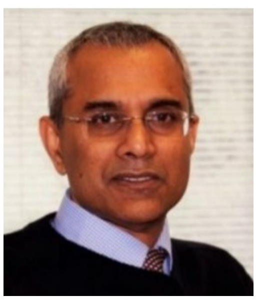
## Structural Robustness in Buildings: State-of-the-Art

**JULY 21, 2020. 1:20 PM – 1:40 PM**

**Sashi Kunnath**
Professor, Department of Civil and Environmental Engineering, University of California at Davis, USA

**Yihai Bao**
University of Alabama at Tuscaloosa

The presentation will provide a summary of research progress in robustness assessment of buildings with the objective of sharing lessons learned and identifying common issues between buildings and bridges. At first, the widely used Alternate-Path-Method (APM) to assess building robustness to progressive collapse is discussed. This is followed by a quick review of advances in computational simulation that was needed to examine the response of buildings at extreme limit states addressing issues related to large deformation behavior of steel and concrete structures. Finally, system-level studies and an approach to assessing overall building robustness against extreme hazards is presented.



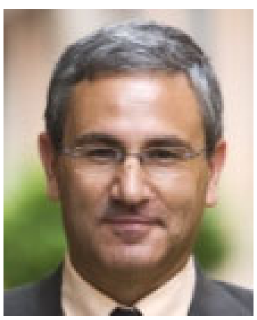
Dr. Sashi Kunnath is currently a professor at University of California at Davis. His main research interests are modeling and simulation of progressive structural collapse, performance-based seismic engineering, development of inelastic material and member models for nonlinear structural analysis, application of low-cycle fatigue concepts in seismic analysis and design, macro-model-based computational tools for nonlinear transient analysis of structures, seismic retrofit and rehabilitation, instrumentation and experimental methods in support of model-based simulation. Dr. Kunnath is the recipient of several awards from ASCE and ACI.

**Bridge Redundancy and Risk Mitigation: the European Approach**

**JULY 21, 2020. 1:40 PM – 2:00 PM**

**Joan Ramon Casas**
Professor of Bridge Engineering. Technical University of Catalunya.
UPC-BarcelonaTech Barcelona, Spain

The Eurocodes are the structural design codes in Europe for bridges and all other structures. In the development of the Eurocodes the concepts of redundancy and risk are integrated under the concept of robustness. The design guidelines for robustness according to the actual Eurocodes are very general and not specific of bridge structures. In the actual revision of the Eurocodes, the requirements for robustness should be improved, not only for new but also for existing structures. The presentation will show how robustness is now implemented in the Eurocodes in general and for bridges in particular and how the new generation of Eurocodes are dealing with the proposed improvement of designing for robustness. A series of proposed metrics to measure the level of structural robustness will be also presented. Finally, a novel approach is shown, where the multi-hazard environment can be considered not only from the point of view of un-expected extreme events (actions) in the robust design of new structures, but also from the feasibility to consider the robustness in the risk management of existing structures subject to environmental degradation.



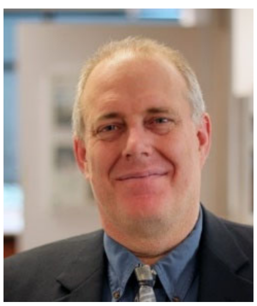
Dr. Joan Ramon Casas is a professor of Bridge Engineering at Technical University of Catalunya. His main research interests are Robustness and redundancy of concrete structures, live load modelling, bridge management systems, advanced non-destructive techniques in bridge evaluation, repair and strengthening of existing bridges with advanced materials, long-term performance and life-cycle analysis of bridges. Dr. Casas is the recipient of several awards from ICE, IABMAS, UPC and IABSE. Dr. Casas is the Secretary General of IABMAS since 1999.

## Canadian Perspective on Addressing Redundancy in Long Span Bridges

**JULY 21, 2020. 2:00 PM – 2:20 PM**

**Darrel Gagnon**
Vice President and Technical Director
COWI North America Ltd.

The presentation will describe how redundancy in long span bridges is treated in the Canadian bridge design and evaluation (load rating) standard. A focus will be placed on the higher significance attributed to redundancy for bridge evaluation of compared to new bridge design. Many traditional means for demonstrating redundancy are difficult or costly to employ in many types of long span bridges. This has led to development of other innovative approaches for providing or improving redundancy for various long span bridge components or structural systems. Methods discussed will include ways of demonstration of alternate load paths, approaches for establishing that internal redundancy exists in a bridge component, designing for a higher level of structural safety, use of protection measures to provide redundancy and prevention of progressive collapse. Brief case studies will be presented for each of these approaches.



Darrel Gagnon currently leads the development of bridge loading and bridge evaluation provisions for the Canadian Highway Bridge Design Code, including long span bridge provisions and he been continuously involved in these areas of this standard for over 30 years. During his long career with COWI, he's designed, inspected, evaluated and rehabilitated numerous types of long span bridges throughout North America

**ALP and Redundancy of long-span truss bridges**

**JULY 21, 2020. 2:40 PM – 3:00 PM**

**Anil Agrawal**
Herbert G. Kayser Professor of Structural Engineering, Dept. of Civil Engineering,
The City College of New York, New York, NY 10031

This presentation features an extensive investigation on the load-path redundancy of long-span truss bridges, including quantification of ALP, defined as the spectra of surrounding members undergoing load redistribution to prevent bridge collapse after sudden damage to a member or members. This research developed an integrated framework to quantify ALP of long-span truss bridges in terms of demand-to-capacity ratio (DCR) for linear elastic analysis and strain ratio for nonlinear dynamic (NLD) analysis. Results of the member removal analysis showed that the three-dimensionality of truss bridges, stemming from upper and lower braces, side trusses, floor beam trusses, and the deck, plays a primary role in protecting the bridge from collapse after removal of a member or members. Simulation results showed that the stress contribution to DCR changes from primarily axial to predominantly moment (both in-plane and out-of-plane) for truss members affected by sudden removal of another truss member. This change occurs because the superstructure tends to undergo torsional motion about its longitudinal axis due to the asymmetrical geometry created after removal of a member. Upper and lower braces and floor truss systems resist this torsional motion, thereby redistributing the load among truss members. The typical member strengthening approach used during seismic retrofit had limited effectiveness in improving ALP of long-span truss bridges; however, retrofits that involved member strengthening as well as adding new members as braces or parts of floor trusses (i.e., members that enhance the three-dimensionality of the bridge) were the most effective and added the least amount of additional weight. NLD analysis using LS-DYNA software resulted in more cost-effective retrofit than linear dynamic analysis using SAP2000 software.

Dr. Anil Agrawal is currently a Herbert G. Kayser Professor of Civil Engineering at the City College of New York and the Chief Editor of the ASCE Journal of Bridge Engineering. He has been the past-chair of ASCE Committee on Bridge Inspection, Rehabilitation and Monitoring. His research interests include inspection and deterioration of bridge elements, robotic inspection of bridge components, post-hazard assessment using drones, behavior of bridges during extreme hazards such as earthquakes, blast, fire, and vehicular impacts on highway bridges, redundancy of long span cable supported bridges and advanced geophysical methods on foundation characterization. He is recipient of 2019 Richard R. Torrens Award for outstanding performance as editor of the Journal of Bridge Engineering, one of ASCE's 35 journals, and 2020 Arthur M. Wellington Prize for the paper, "Heavy Truck Collision with Bridge Piers: Computational Simulation Study," Journal of Bridge Engineering, June 2019.

## Recent Guide Specifications and Design Aids for Redundant Member Analysis

**JULY 28, 2020. 10:05 AM – 10:25 AM**

**Matthew H. Hebdon**
Assistant Professor, Charles E. Via Jr. Department of Civil & Environmental Engineering,
Virginia Tech, Blacksburg, VA, 24060, USA

There has been much effort in recent years to better understand the redundancy of steel bridge systems and members. The results of this effort have shown that owners of steel bridges may benefit from a closer look at how redundant load paths can prevent failure. Two AASHTO Guide Specifications were published in 2018 to facilitate the analysis of redundancy in the evaluation of steel bridges: The Guide Specifications for Analysis and Identification of Fracture Critical Members and System Redundant Members, and the Guide Specifications for Internal Redundancy of Mechanically-Fastened Built-Up Steel Members. This presentation will discuss an overview of the key components of the guide specifications, when they are applicable, and how to implement their use. In addition, a design aid, the IRM (Internally Redundant Member) Evaluator has been developed to assist engineers in evaluating members for internal redundancy in both axial and flexural loading conditions. This presentation will also highlight the application of the IRM Evaluator tool and how it can facilitate the application of the Guide Specification for internal redundancy. The use of this free tool can dramatically reduce the effort required to understand the capacity of a member, as well as an appropriate inspection interval to ensure the safety of the structure. Owners may utilize this tool to better understand the capacity of built-up members and prioritize inspection intervals and resources through the use of a rational inspection interval based on fatigue crack growth models.

Dr. Matthew H. Hebdon is an assistant professor in the Charles E. Via, Jr. Department of Civil & Environmental Engineering at Virginia Tech. His research is on inspection, evaluation, and analysis of bridges and structures. He is working on incorporating autonomous control of UAVs in close proximity to structures with turbulent air flow to relay critical inspection data with high levels of detail for 3D model generation, machine learning, and time history monitoring and evaluating of deterioration in difficult-to-access area. He is also currently working on several research projects targeting methods to improve the capacity and life-span of bridge structures.

## Assessment of structural redundancy in Honshu Shikoku Bridges

**JULY 28, 2020. 10:25 AM – 10:45 AM**

**Imai Kiyohiro**
Senior Director, Corporate Planning Department, Honshi-Shikoku Bridge Expressway Co. Ltd.

Honshu Shikoku Bridges connect between Honshu and Shikoku islands by three routes in Japan. There are seventeen long span bridges in the three routes including 10 suspension bridges, 5 cable stayed bridges, one truss bridge and one arch bridge. Long span bridges are defined as a bridge with a span length of more than 200m in Japan. These bridges were completed in the last century, so all of these bridges are designed according to the allowable stress design method.

In order to evaluate the reliability of these bridges, one of the suspension bridges was selected and investigated by element as well as system reliability analysis. In addition, since consideration to earthquake load is important for bridge design in Japan, the structural redundancy of another one of the suspension bridges was investigated with considering huge earthquakes such as 2 or 4 times of the design earthquake loads. After the Kobe earthquake in 1995, a new seismic design code was established to take into account seismic performance level with considering the two levels of earthquakes. In order to improve the seismic performance of the bridges against two levels of earthquake loads, two examples are introduced in the presentation.

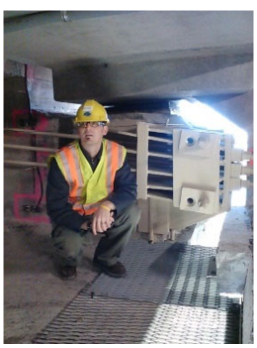
Dr. Imai Kiyohiro holds a bachelor's and master's degree in civil engineering from Kyoto University, a doctor's degree in civil engineering from the University of Colorado, Boulder. He has been with the Honshu Shikoku Bridge Expressway Co., Ltd for over 30 years and currently serves as the Senior Director of Corporate Planning Department. He has been a member of Road Bridges committee in PIARC (World Road Association) since 2008.

## Redundancy Perspective for Gordie Howe Bridge

**JULY 28, 2020. 10:45 AM – 11:05 AM**

**Matt Chynoweth**
Chief Bridge Engineer, Michigan Department of Transportation

When complete, the Gordie Howe International Bridge will be the longest cable-stayed bridge on the continent of North America. When developing the specifications for the overall Project Agreement, the Windsor Detroit Bridge Authority (WDBA), Michigan Department of Transportation (MDOT), and our Owner's Engineer Consultant, Parsons, had to consider relevant requirements of both the Canadian Bridge Design Standards, and U.S. Bridge Design Standards for cable supported bridges, to ensure an adequate approach to all steel tension members and connections being designed with appropriate redundancy. A site specific notional live load was developed for bridge design, which includes weigh-in-motion data, and the live load on the bridge is to be applied as commercial vehicle lanes, and mixed vehicle lanes. Using the notional live load model, redundancy is to be achieved either through load path redundancy, or internal redundancy, and overall, the bridge must be designed with ductility that can sustain the bridge with noticeable signs of deformation or distress after any portion of a tension member fails. In addition to the bridge requiring to meet Post Tensioning Institute (PTI) standards for stability during cable loss, members must be proportioned to address permanent locked-in effects from erection loads, dynamic forces due to the energy release from member loss, and capacity-to-demand rations for all members at the ultimate limit state greater than or equal to 1.0. In addition, due to the complex nature of the bridge superstructure system, and the need for finite element modeling of load distribution and member failure, the main superstructure tension elements are to be designated as System Redundant Members (SRMs), and subject to robust fabrication practices. This will ensure the superstructure will not be NBI designated as fracture critical and eliminate the requirement of fracture critical inspections during the bridge's service life.



Matthew J. Chynoweth is the Chief Bridge Engineer at Michigan Department of Transportation and the Director of MDOT Bureau of Bridges and Structures. He has 16 years with MDOT and 4 years with consulting firm prior to joining MDOT, responsible for all aspects of bridge design, construction, preservation, and asset management for the State of Michigan. He is also Executive Committee Member of the AASHTO Committee on Bridges and Structures, Chair of Technical Subcommittee T-6, FRP Composites, member of Technical Subcommittee T-4, Bridge Construction.

## Design for Redundancy of Long Span Bridges in Multi-Hazard Environment

**JULY 28, 2020. 11:05 AM – 11:25 AM**

**Marwan Nader**
Senior Vice President at T.Y. Lin International

Long span bridges often serve as lifeline structures, their immediate serviceability after a major event and collapse prevention are of utmost importance. The bridges, in a multi-hazard environment, often face not only natural hazards from wind, seismicity, ice, etc., but also extreme accidental and intentional security threats. This presentation will discuss how the designs account for redundancy, through the case studies of two (2) major cable-stayed and self-anchored suspension bridge projects, namely, the 3.4 km new Champlain Cable-Stayed bridge in Montreal and the 3.6 km San Francisco-Oakland Bay Bridge in California. The discussion will focus on accounting for hinging mechanism in seismic response with push-over analyzes, providing redundancy for threats, using more rigorous factor of safety in load combinations for single load path structures, and assigning limited use of fracture-critical members on the bridges.

Dr. Marwan Nader is a Senior Vice President and T.Y. Lin International's Bridge Technical Director. With over 30 years of experience in long-span bridge design and construction, Dr. Nader is the Engineer of Record and Project Manager for the record-breaking San Francisco-Oakland Bay Bridge Self-Anchored Suspension Bridge, as well as the Engineer of Record and Design Manager for the new cable-stayed Samuel De Champlain Bridge in Montreal. He serves as the Chair of the Cable-Supported Bridges ASCE Committee and he is a member of the Transportation Research Board's Steel Bridge Committee. Dr. Nader is a recipient of the 2004 ASCE Arthur M. Wellington Award. In 2014, he was selected for the Distinguished Alumni of the Year by American University of Beirut and is a 2015 inductee of the Civil and Environmental Department Academy of Distinguished Alumni at the University of California, Berkeley. In 2016, IABMAS honored Dr. Nader with the Senior Prize in recognition of his significant contributions to the field of bridge engineering.

## Robustness, Hazards, and Risk Mitigation for Buildings, with Implications for Bridges

**JULY 28, 2020. 11:45 AM – 12:05 PM**

**David Stevens**
Managing Principal, Protection Engineering Consultants, USA

Robustness and collapse resistance in buildings are often implemented through designs that use redundant load paths. This strategy can be straightforward to apply due to the abundance of structural members and foundation elements comprising typical building structures. Load paths may occur through flexural or catenary actions in the horizontal members; catenary action can be of particular advantage as existing structural members can be slightly modified to carry this tensile force. The hazards for a building may be known and therefore quantifiable (e.g., vehicle impact, gas explosion, vehicle bomb), or they may be unknown and thus hard to postulate. For known hazards, the risk to the structure can be mitigated by designing directly for the known loads (i.e., if the location and size of a bomb are known or specified, then the building can be hardened appropriately). Conversely, mitigating risk from unknown hazards often requires a more systemic protective design strategy that leverages redundant load paths, integrity, continuity, ductility, and considers a nominal action or threat as the initiating event.

While both are structures, bridges are unique from buildings in several ways: fewer inherent load paths, less redundancy, fewer foundations and structural supports, no frangible envelope, harder to impose physical standoff, and different hazards. However, the tenets from collapse-resistant building design can be applied to a certain extent to bridges. Differences and similarities in hazards for bridges and buildings are discussed. Conventional collapse-resistant design approaches are evaluated for their applicability to bridge design, and conclusions are drawn relative to risk mitigation in a multi-hazard environment. Applied research needs in the area of multi-hazard bridge design are also discussed.

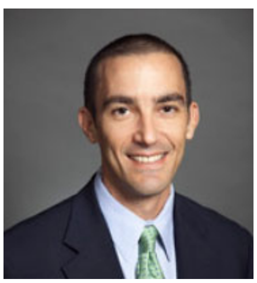
David Stevens is the Managing Principal of Protection Engineering Consultants, a research and design engineering firm with offices in Austin and San Antonio, Texas. David is the primary author of the Department of Defense Unified Facility Criteria 4-023-03 Design of Buildings to Resist Progressive Collapse and is a co-author of the Federal Highway Administration Bridge Security Design Manual.

## Structural Redundancy: Lessons from Past Research and Opportunities for the Future

**JULY 28, 2020. 12:05 PM – 12:25 PM**

**Eric Williamson**
Professor, Department of Civil, Architectural & Environmental Engineering,
University of Texas at Austin, USA

Past experimental research on structural redundancy is presented in which different structures were loaded until total collapse was observed. These previous projects included a fracture-critical steel box-girder bridge and a composite floor system in a typical steel-framed building. In both testing programs, the structures showed greater load-carrying capacity than predicted by current specifications and guidelines. These structures demonstrated resiliency and the ability to develop alternate load paths different from those typically idealized in design. Additionally, observations from accidental impacts against bridges are shown and considered in relation to the experimental test results. Finally, opportunities for improving our current understanding of the factors influencing structural redundancy are discussed.



Eric Williamson is currently a professor at University of Texas at Austin. His main research interests are dynamic response of structures including applications to blast-resistant design and seismic-resistant design, static and dynamic stability, failure modeling and damage mechanics, progressive structural collapse.

## Outcome of AASHTO Breakout Session on Redundancy

**JULY 28, 2020. 12:25 PM – 12:45 PM**

**Jeff Robert**
Division Chief of the new design division of the Office of Structures,
Maryland Department of Transportation

This presentation will discuss the outcomes of AASHTO Session on July 23, 2020 on redundancy of bridges.

Jeffrey Robert is currently the Division Chief within the new design division of the Office of Structures at the Maryland State Highway Administration's Office of Structures. He has served on AASHTO's Committee for Bridges and Structures for ten years and currently is the chair of the Loads technical committee.

## Redundancy Aspects of the FIU Bridge Collapse

**JULY 28, 2020. 12:45 PM – 1:05 PM**

**Sherif El-Tawil**
Antoine E. Naaman Collegiate Professor of Civil and Env. Engineering,
Dept. of Civil & Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125, USA

On March 15, 2018, a pedestrian concrete truss bridge in Miami, FL, collapsed during construction. The failure of this bridge caused multiple casualties and raised many serious concerns regarding the design and construction of the bridge, especially the bridge redundancy for the single-row concrete truss bridge. In this presentation, high fidelity computational simulation is used to investigate the behavior of critical structural members of the bridge during construction. Based on simulation and demand/capacity analysis, this work shows the horizontal component of the re-tensioning force overcame the resistance of the northern end joint and caused it to slide with respect to the deck. As sliding progressed, dowel action between the deck and joint became fully mobilized, crushing and damaging concrete locally within the joint and the deck. The evolving damage (to the cold joint and adjacent joint and deck concrete) prompted more sliding and led to a vicious cycle that culminated in the collapse of the entire bridge. The robustness of the bridge design was evaluated in the simulations by changing the coefficient of friction at the cold joint and conducting tendon removals in the tensional members of the bridge. The results from the analysis and simulations provide important insights into the collapse mechanism and highlight lessons that could be learned for preventing similar catastrophic failures in the future by ensuring bridge redundancy and robustness.

Dr. Sherif El-Tawil is Antoine E. Naaman Collegiate Professor of Civil and Environmental Engineering Department at the University of Michigan, Ann Arbor. Dr. El-Tawil's general research interest lies in computational modeling, analysis, and testing of structural materials and systems. He is especially interested in how buildings and bridges behave under the extreme loading conditions generated by manmade and natural hazards such as seismic excitation, collision by heavy objects, and blast. A Fellow of the American Society of Civil Engineers, Dr. El-Tawil is Editor-in-Chief for the Society's Journal of Structural Engineering. He is recipient of the Korean Concrete Institute's Paper of the Year Award and ASCE's State-of-the-Art Award, Huber Research Prize, Moisseiff Award (twice), Wellington Prize, Torrens Award, and Norman Medal.

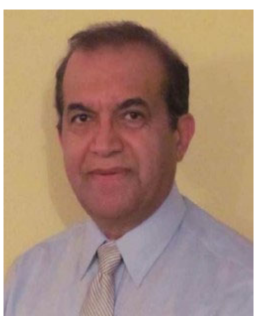
## State of Practice on Redundancy of Long Span Bridges and AASHTO Requirements

**JULY 28, 2020. 1:05 PM – 1:25 PM**

**Bijan Khaleghi**
State Bridge Design Engineer, Washington State Department of Transportation
Bridge & Structures Office, Olympia, WA 98504-7340, USA

Redundancy in the AASHTO LRFD Bridge Design Specifications is considered during design by using load modifiers factors on the load side of the equations. However, the value of load modifiers is determined by judgment rather than through a calibration process. The LRFD Bridge Evaluation manual defines bridge redundancy as the capability of a bridge structural system to carry loads after damage to or the failure of one or more of its members. The System reliability encompasses redundancy by considering the system of interconnected components and members. Quantification of redundancy is not fully formulated for long span bridges. Rupture or yielding of an individual component may or may not mean collapse or failure of the whole structure or system.

To ensure uniform system performance for different bridge configurations, geometrical arrangements, and material and structure types, system factors are proposed in NCHRP Report 776 "Bridge System Safety and Redundancy". The NCHRP report provides design provisions and implementation examples of redundancy analysis of long span bridge types including truss bridge, steel bridge, prestressed concrete bridges, under vertical load, and under lateral point load. The report provides system factors that can be used during the design and safety assessment of bridges subjected to lateral load using the displacement-based approach similar to the seismic design specifications. This presentation focuses on the redundancy requirement of the LRFD Specifications and the recommendations of the NCHRP report 776 in developing a methodology to quantify bridge system reliability for redundancy.



Dr. Bijan Khaleghi is the State Bridge Design Engineer with the Washington State Department of Transportation Bridge and Structures Office, and adjunct professor at Saint Martin's University. He is a member of AASHTO Technical Committees on Movable Bridges T-8, Concrete Bridges T-10, Tunnels T-20, Roadway Tunnels, and member representative of AASHTO at the Permanent International Association for Road Congress (PIARC). Bijan is a member of TRB AFF00-2 Accelerated Bridge Construction and AFF30 Concrete, AFF60 Tunnels. He is also a member of American Segmental Bridge Institute (ASBI), Precast/Prestressed Concrete Institute (PCI), and National ABC Center at FIU. Bijan is recipient of PCI Robert J. Lyman award, October 2018, PCI Fellow Award, February 2018, ASCE T.Y. Lin Award, March 2014, Charles C. Zollman Award, PCI Journal 2011 and 2013, ASCE SEI T.Y. Lin Award, May 2006, Martin P. Korn Award, PCI Journal Award 2005.

# Parallel Breakout Sessions

**JULY 28, 2020. 2:00 PM – 3:50 PM**

## Session 1: Are redundancy considerations sufficient in current design codes, such as AASHTO?
## (Chair: Wagdy Wassef)

Wagdy Wassef is an Engineering Director with WSP. He has over three decades of diversified experience on different aspects of bridges analysis, design, rehabilitation and research. Dr. Wassef has been active in updating AASHTO LRFD since the specifications was adopted in 1993. He authored many of the revisions to the specifications including the current wind load provisions, Section 15, sound barriers, and the revisions to the service limit state load factors for prestressed concrete.

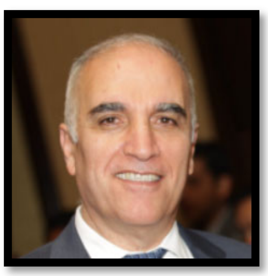
## Session 2: Member based analysis versus system criticality.
## (Chair: Dr. Baidurya Bhattacharya)

Dr. Baidurya Bhatacharya is currently a professor at the Indian Institute of Technology Kharagpur. His research interests include material degradation and probabilistic mechanics. Over the years, Bhattacharya has worked on load modelling, time-dependent reliability analysis, system reliability and progressive collapse, target reliabilities, LRFD based design and evaluation criteria, microstructural damage growth, heat conduction, damage detection and system identification problems. He has applied these variously to nuclear power plant reactors and containments, buildings, bridges, ship and offshore structures. He served as Associate Editor of the Journal of Bridge Engineering ASCE for eight years. He is a Fellow of the Indian National Academy of Engineering and a Fellow of the American Society of Civil Engineers.

## Session 3: Current simulation technology during the design process.
## (Chair: Dr. Sherif El-Tawil)

Dr. Sherif El-Tawil is Antoine E. Naaman Collegiate Professor of Civil and Environmental Engineering Department at the University of Michigan, Ann Arbor. Dr. El-Tawil's general research interest lies in computational modeling, analysis, and testing of structural materials and systems. He is especially interested in how buildings and bridges behave under the extreme loading conditions generated by manmade and natural hazards such as seismic excitation, collision by heavy objects, and blast. A Fellow of the American Society of Civil Engineers, Dr. El-Tawil is Editor-in-Chief for the Society's Journal of Structural Engineering. He is recipient of the Korean Concrete Institute's Paper of the Year Award and ASCE's State-of-the-Art Award, Huber Research Prize, Moisseiff Award (twice), Wellington Prize, Torrens Award, and Norman Medal.

## Session 4: Role of hazards in redundancy considerations.
## (Chair: Dr. Hani Nassif)



Dr. Hani Nassif is a professor of Civil and Environmental Engineering at Rutgers University, and currently the Director of the "Bridge Resource Program (BRP)", sponsored by New Jersey Department of Transportation (NJDOT). He is also serving as the Associate Director for Outreach and Technology Transfer, for the newly established Tier 1 Center (2017-2021), "Connected Cities for Smart Mobility toward Accessible and Resilient Transportation (C2SMART)" led by NYU. He also served as the associate Director for the Center on Research on Concrete Application for Sustainable Transportation (RE-CAST), another Tier 1 University Transportation Centers (UTCs) led by Missuori University for Science and Technology (MUST) (2013-2018) to address the U.S.DOT's strategic goal of State of Good Repair. He is a Fellow of the American Concrete Institute (ACI) and past member of its Technical Activity Committee (TAC) and served as the President of the New Jersey ACI Chapter. He received various awards including the Lifetime Achievement Award from the NJACI Chapter and Concrete Aggregate Association, AASHTO's Research Activities Committee (2013) "Sweet Sixteen", Project Implementation Award from NJDOT (2013 and 2017), American Council of Engineering Companies (ACEC) Educator of The Year Award (2006) and American Society of Civil Engineers (ASCE) Central New Jersey's Educator of The Year Award (2005).