# EVALUATION OF AGING SLAB-ON-GIRDER BRIDGE RESILIENCY AFTER AN EXTREME CLIMATE EVENT USING ACCELERATED BRIDGE CONSTRUCTION

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## ABSTRACT

A large number of bridge structures in North America are failing due to the combined excessive traffic loads and extreme climate events. Therefore, there is a need to enhance the resilience of aging bridges to ensure life safety and to minimize the risk of traffic distribution. This study is aimed at evaluating the resiliency of critical elements and the overall bridge system when subjected to changing climate and after an extreme climate event. The accelerated bridge construction (ABC) approaches to be incorporated for the repair of partially damage bridges or the replacement of fully damaged or collapsed bridges.

## INTRODUCTION

Among the most popular short span bridge types in North America is the slab-on-girder bridges, where they have the benefits of simplicity in design, fast in construction, and the traffic-induced vibrations of the superstructure are reduced through dampers; the vibration that is transmitted to the substructure is further reduced due to the discontinuity of the superstructure/substructure joints. Increased traffic loads, coupled with the deterioration of bridges structural components due to reinforcement corrosion and other ageing processes, cause interactive and progressive damage in different structural elements. It is reported that structure deteriorations are caused by different physical, mechanical and chemical processes depending on the bridge location, environmental and operational conditions. Physical and chemical deterioration are influenced by changing climate resulting in accelerated deteriorations of the bridge elements' structural performance. Consequently, the performance and capacity of concrete and steel bridge structures are significantly affected by changing climate in terms of their safety and serviceability, in the long term, or in extreme loading. Consequently, these reductions of ultimate capacities of bridge components due to accelerated deterioration increase the vulnerability of bridge structural system to sudden collapse when the bridge system is subjected to extreme loads/ events.

Climate change is also correlated to the observed increase in frequency and magnitude of extreme climatic events, and hence, resulting in a rise of extreme climatic loads on bridges (Wang et al. 2010 [1]). Bridges could be significantly impacted by climate changes, through the increase in average temperatures, and increases in the frequency and magnitude of extreme climate events such as hot and cold waves, and storms or hurricanes. The changes in ambient and differential temperatures may lead to significant changes in the structural response of the bridge components and structural systems in terms of large deformations and high-stress levels that could exceed those allowed by existing design codes. Such effects could affect the structural integrity of the bridge system, for example; substantial differential temperature could result in damaging the composite action between the slab and girders in slab-on-girder bridges. The response of bridges to the changes in temperature caused by climate change could lead to a significant change in deformations and stresses. Also, bridges subject to extra stresses through thermal expansion & increases movement.

The climate change have been evidenced to accelerate the temperature fluctuation, freezing- thaw cycles, heat and/or humidity waves, which could highly accelerate the bridge deterioration-and-rehabilitation cycles. There is growing awareness worldwide that climate change will have significant impacts on the performance and resilience of transportation infrastructure, where bridges represent key links of the transportation networks. The intensification in frequency and/or the intensity of extreme weather events are now obvious. That future climate changes may lead to different climatic loads on infrastructure, which in turn will lead to reduced safety, loss of serviceability, shortened service life, long service disruption, high rehabilitation and replacement costs, and significant negative socio-economic impacts. Therefore, evaluation of the instantaneous residual capacity and hence identifying the safety and serviceability of the bridge elements and structural system will enable an expedited assessment of the bridge state after a major extreme climate event. The resiliency of bridges in terms of recovery after major climate events would also involve the required level of load capacity to enhance of bridge performance avoiding its collapse under similar extreme event. This would result in ensuring the life safety and minimizing the risk of traffic distribution due to lane or complete bridge closures, and/or bridge posting.

The objective of this paper is to investigate the effects of accelerated construction/rehabilitation approaches on the enhancement of an aged slab-on-girders bridge resiliency. This resiliency enhancement is in terms of minimum recovery time when the bridge is damaged or collapsed due to accelerated deterioration with the changing climate, or an extreme climate event. The investigation is aimed at evaluating the resiliency of critical elements and the overall bridge system when subjected to changing climate and after an extreme climate event. Already developed 2D non-linear FEM model based on staged deterioration mechanisms is used to simulate the structural performance of aging slab-on- prestressed concrete girders bridge.

## RESILIENCY OF DAMAGED CRITICAL BRIDGE ELEMENTS AND SYSTEMS

A resilient infrastructure system can be defined as a system that provides adequate performance against cumulative damage and extreme climatic event or stresses at an acceptable cost over its life cycle (Lounis and McAllister 2016 [2]). Resilience of civil infrastructure, such as bridges, is usually associated with the ability to deliver a certain service level even after the occurrence of an extreme event and to recover the desired functionality as fast as possible (Bocchini et al. 2015 [3]). Following excessive an extreme climate event, there is need to restore the structural performance of the bridge system to a prevent level or even to a higher performance level. In Figure 1, the blue line (solid and the dotted) represents the time history of the bridge, where its performance decreasing due progressive accumulation of damage in the bridge elements over their service life. The dotted part of the blue line represents the performance of the element if no sudden significant damage (or collapse) occurs due to an extreme event. If a significant drop of the performance due to an extreme climate event occurs, then service life of the bridge might be ended. The bridge replacement would take place, however, the required level of performance and load capacity would be changed targeting a longer service life and a higher resiliency as shown in the green lines of Figure 1.

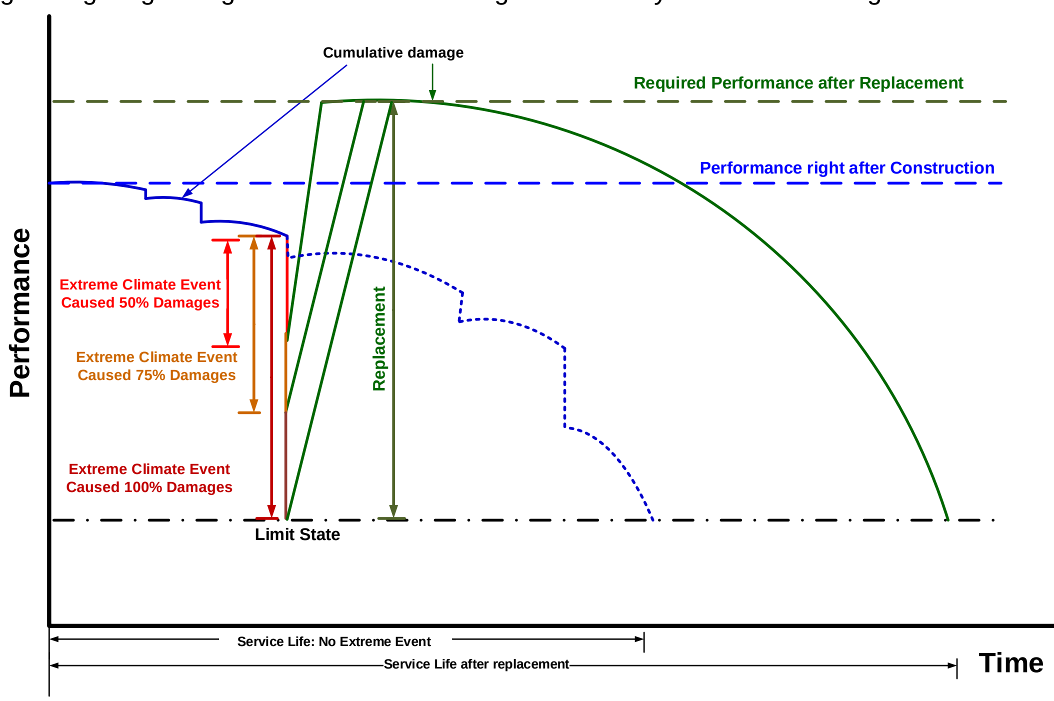


Figure 1: Schematic representation of resilient a bridge structural system

Under the previous definition of resilient structural systems, a resilient critical element of a highway bridge should provide a long service life, adequate robustness and minimal disruption of traffic with minimum life cycle cost. When an aged bridge that is affected by cumulative damages is subjected to an extreme climatic event (e.g. flood-scour, flood-ice impact, extreme ice accretion, extreme cold and heat wave), then either its structural performance dropped partially or fully (Figure 1). Then the structural performance of the element and/ or the structural system needs to be recovered either to the initial design capacity or higher. Figure 2 shows the major performance parameters of a resilient bridge element, which are the load capacity, ductility, and short recovery time. Integration of accelerated construction approaches for the rehabilitation and/ or replacement would result in fast recovery of the structural performance as shown in Figures 1 & 2. The precast-prestressed approach presents an accelerated manufacturing that will lead to deliver the required bridge element to the site in the shortest possible time. With a suitable accelerated bridge construction (ABC) in site, the recovery of service and securing the required structural performance can be achieved. Hence, the bridge resiliency is rapidly enhanced through the short recovery time targeting acceptable performance.

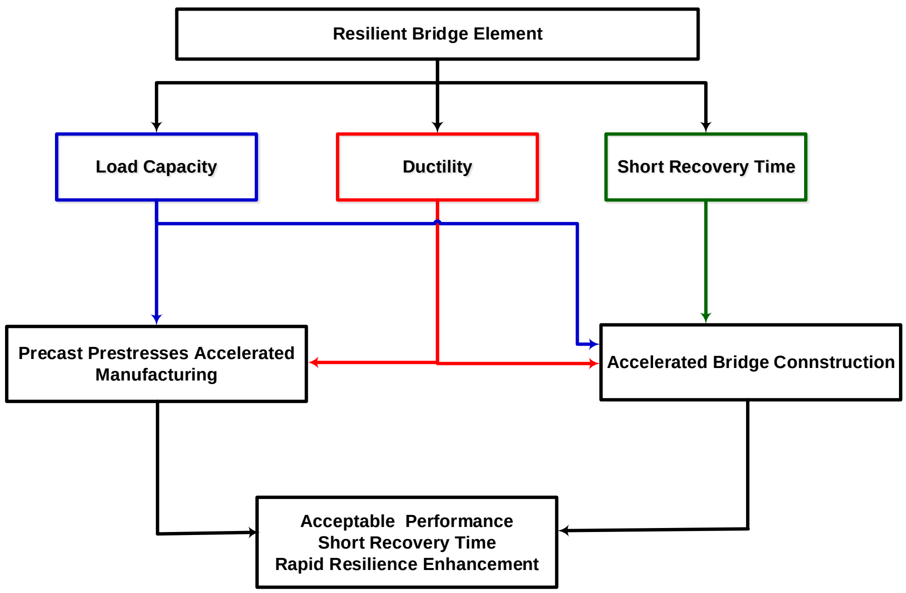


Figure 2: Framework for resilient bridge element

## ESTIMATION OF RESIDUAL CAPACITY AND SAFETY OF DETERIORATED RC BRIDGE ELEMENTS

The developed 2D non-linear finite element model, FEM, model based on staged deterioration mechanisms is used, Almansour et al. 2018 [4]. The model introduces three measures of bridge resilience, namely load carrying capacity, ductility and rapid recovery of function. Essentially, it is proposed to simulate the multi-stage failure of beam-columns where the inelastic nonlinear sectional analysis as part of nonlinear finite element analysis is performed. The effect of sectional geometry, steel reinforcement and confinement of core concrete are considered in the sectional analysis level while the effect of the boundary conditions and loading patterns are applied in the structural analysis level.

The developed FEM is based on the following assumptions: (i) the concrete and steel are isotropic materials; (ii) the "local" stiffness matrix (with its 6 x 6 entries related to 3 degrees of freedom for each of the two nodes in each finite element) is established from the average of the axial and the flexural rigidities calculated over all the characteristic sections of that element; (iii) the flexural rigidity of each section is calculated from the base sectional analysis; (iv) all deformations (displacements, rotations, etc.) are continuous functions over the discretized continuum (structural element or structural system) throughout all loading steps; (v) Euler-Bernoulli beam theory is applicable in all levels of the combined gravity loads and reinforcement corrosion damage states; (vi) the model considers the instantaneous stress redistribution due to the bond loss in the corrosion damaged zone; and (vii) equilibrium is satisfied at the section level, where the instantaneous axial and flexural rigidities are effectively transferred to the element level in order to establish the instantaneous element stiffness, and hence the global stiffness of the structure at each load step. The element stiffness matrix is established using the cross-section properties at the sectional level where the forces and stiffness are calculated using numerical integration, (Mohammed 2014[5]).

Nonlinear finite element procedure typically involves load increments. The material and geometrical properties of the elements and their characteristic sections are variable with the progress of the load increments. The equilibrium of the developed model is satisfied in every element, every section, and overall the structural system, where the numerical stability of the model and its sensitivity to the load increments, number of elements, number of sections per element, and number of cycles in the iterative approach are key parameters in the evaluation of the numerical efficiency of the finite element model, (Mohammed 2014[5]).

**CASE STUDY**

A typical slab-on-girders bridge has been considered. The bridge is a single span of 40.0m length measured between the centers of the bearings at the bridge two abutments. The platform width is 15.0m, which accommodate three lanes (as per the Canadian Highway Bridge Design Code - CHBDC 2014) of a CL-625 Truck live load; where the width of each lane is 3.75m. The wearing surface is assumed 90mm thick bituminous overlay, haunch is 75mm, shoulder width is 2.5 m and shoulder width on bridge is 2.0m. The bridge is assumed to have no skew or in plan curvature. The bridge superstructure consists of six pre-stressed concrete CPCI 1400 girders with height of 1.4m compositely integrated with a 0.225 m thickness reinforced concrete slab and the center-to-center spacing between girders is 2.5 m. Sectional view of the superstructure and girders is shown in Figure 3. As the detailed design characteristics of this bridge is out of the scope of this study, the focus of this paper is on the impact of accelerated construction/rehabilitation approaches on the enhancement of the bridge resiliency.

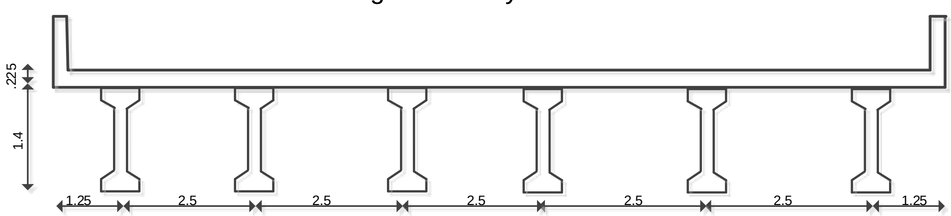


Figure 3: Elevation view of a slab-on-girders bridge (a deck with 6 girders); dimensions in m

In order to investigate the most sever failure cases that the bridge is likely subjected to during an extreme climate event, three possible scenarios are considered: (i) the bridge superstructure would be partially damage where two girders assumed to be failed; (ii) the bridge superstructure would be partially damage where three girders assumed to be failed; and (iii) the bridge would fully collapse where its substructure assumed to be failed.

As shown in Figure 4, the bridge has its full capacity as constructed when affected by the climate event (its capacity is 45,000kN.m, blue line). In each case of the two first scenarios where the bridge superstructure partially damage, the bridge capacity is calculated; in case (i) where two girders are failed, the bridge capacity is 30,500kN.m (which is almost 70% of original capacity; purple line); of course in this case and due to partial failure, the bridge width is decreased which would lead to close one or two lane traffic, however, the bridge is still under service; also, at this stage, the bridge would be repaired and recovered to have its full capacity and original performance avoiding any extra reduction and/or posting. In addition, in case (ii) where three girders are failed, the bridge capacity is 23,000 kN.m (which almost 50% of original capacity is; brown line). Again in this case and due to partial failure, the bridge width is more decreased where only one lane is under service; also, at this stage, the bridge would be repaired and recovered to have original performance.

In scenario (iii) where the bridge fully damage due to its substructure failed, two cases of damaged could be considered: case 1: one or two columns (pairs) are failed, and case 2: the superstructure is shifted due to scour and/or instability of the substructure; Figure 4 shows extreme climate event caused 100% damages where the bridge lost totally its capacity (red line). In both cases, the bridge is totally failed and posting of service (traffic closure), also, fast recovery is mandatory where replacement of the bridge substructure is considered, green curve in the Figure 4. This will lead to ensure the bridge safety and serviceability.

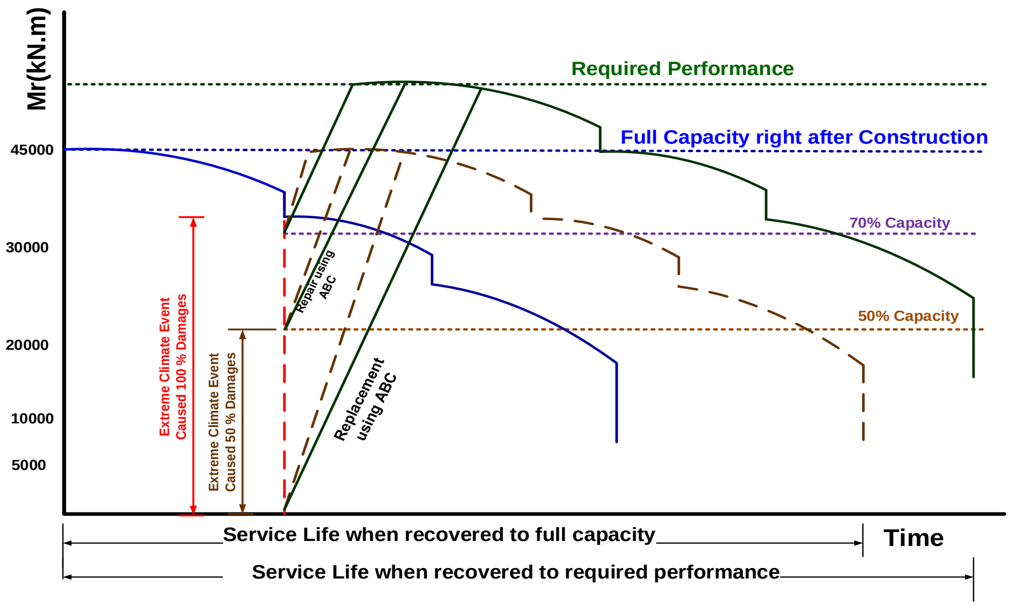


Figure 4: Relation of resilient the bridge system and rapid recovery to functionality using repair/ replacement ABC

## IMPACT OF ACCELERATED CONSTRUCTION APPROACHES ON THE BRIDGE RESILIENCY

As shown in Figure 4 and previous section, it is assumed that three scenarios would resulted in partial damage or full collapse of the bridge. The three scenarios are quantitatively result in: (i) losing 30% of the bridge full capacity (the remaining capacity is 70% of the bridge design capacity); (ii) losing 50% of the bridge full capacity; or (iii) full collapse of the bridge. The recovery plan and the required capacity after the climate extreme event will be decided by infrastructure owners based on the bridge importance to the transportation network. Bridges are suggested to be categorized after a major disaster into three types based on their importance: (i) very important bridges-recovery should be immediate, where their operation is extremely important to first responders, hospitals and other essential service centers; (ii) important bridges-recovery should be fast, where their operation is important for people everyday life economically important; and (iii) other bridges, where their operation is important for economic activities and recovery of all urban activities.

The recovery time is also affected by the required performance of the bridge after an extreme event. Figure 4 shows two performance levels as a target of the performance recovery plan: (a) recovery of the bridge structural performance to the original performance level (brown lines); (b) recovery of the bridge structural performance to a higher performance level based on the bridge importance and the required load capacity (green lines). The slop of the inclined lines that are related to each damage level represent the speed of the recovery to the specified structural performance level. Figure 4 shows that if the required performance level is higher than the original design level (or after construction level) then the service life of the bridge likely to be longer.

This study suggested the accelerated bridge construction (ABC) approaches to be incorporated for the repair of partially damage bridges or the replacement of fully damaged or collapsed bridges. Precast prestressed concrete components are to be used for the replacement of all damaged bridge elements. This would reduce the negative impacts that construction operations have on traffic flow (Palermo and Mashal 2012[6]).

## SUMMARY AND CONCLUSIONS

Global changes in temperature, precipitation and wind patterns threaten the integrity and functionality of reinforced concrete highway bridges. A large number of existing bridge structures in North America are vulnerable to failure due to the combined excessive aging/ deterioration and extreme climate events, including flood and resulting scour, wind, and ice loads. Hence, there is a need to enhance the resiliency of aging bridges to ensure life safety and to minimize the risk of traffic distribution due to lane closures, and/or bridge posting. In this context, this study investigates the effects of accelerated construction/rehabilitation approaches on the enhancement of an aged slab-on-girders bridge resiliency. The focus is on evaluating the resiliency of critical elements and the overall bridge system when subjected to changing climate and after an extreme climate event where the resiliency enhancement is in terms of minimum recovery. The study used already developed 2D non-linear FEM model based on staged deterioration mechanisms. A typical slab-on-girders bridge designed according to CHBDC is considered. Three possible scenarios of sever failure cases, that the bridge is likely subjected to during an extreme climate event, are considered. The first scenario is the bridge superstructure would be partially damage where two girders assumed to be failed, and remaining capacity is 70% of the bridge design capacity; the second scenario is (ii) the bridge superstructure would be partially damage where three girders assumed to be failed, and remaining capacity is 50% of the bridge design capacity; and the third scenario is the bridge would fully collapse where its substructure assumed to be failed.

From the case study, it is found based on the bridge importance to the transportation network, the recovery plan and the required capacity (after the climate extreme event) will be decided by infrastructure owners. After a major disaster, bridges are categorized into three types based on their importance and operation for economic activities and recovery of all urban activities. The categorized bridges are very important bridges, important bridges, and other bridges. In addition, the study suggested the accelerated bridge construction (ABC) approaches to be incorporated for the repair of partially damage bridges or the replacement of fully damaged or collapsed bridges.

As part of a large on-going research project at the National Research Council Canada, Construction Research Centre, different advanced materials and accelerated construction/rehabilitation approaches will be explored through a comprehensive parametric study applied to different types of bridges.

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