RESILIENCY ENHANCEMENT OF AGING FRAME BRIDGE USING ACCELERATED BRIDGE CONSTRUCTION AS AN EFFECTIVE CLIMATE CHANGE ADAPTATION APPROACH

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ABSTRACT

Frame Bridge is a cost-effective alternative to the conventional arch bridge. A severe climate event could result in partial or full damage of the bridge. The recovery time is affected by the required performance of the bridge after an extreme event. 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 frame bridges as it provides the highest possible recovery time versus classical in-site construction approach.

INTRODUCTION

Frame bridge was a common bridge type in North America since its development by mid 1920s as a cost-effective alternative to the conventional arch bridge, which requires massive abutments and significant excavation/grading to accommodate its relatively high profile . The strength of a concrete rigid frame bridge originated from the rigid connection of the vertical abutment walls with the horizontal deck slab, resulting in a shallow mid-span section. This bridge type has the ability to redistribute the loads through the structure until it reached a balance when any one element of the bridge is overstressed. Its immense strength and rigidity provides an additional safety to the structural system. The result is a bridge that provides greater structural strength and redundancy than reinforced concrete slab-on-girder bridges. However, they have many disadvantages such as their construction complexity, high construction cost, and the difficulty in evaluating their structural performance when attacked by reinforcement corrosion or they have material deficiencies. Also, the structural continuity of the frame bridge may increase its sensitivity to vibration when severe damage is induced in the super- and/or the sub- structures. By the 1930s and 1940s, these structures became more popular for river crossings and grade separations. Short and medium span rigid frame concrete bridges are still widely used today for rail/roadway grade separations in urban areas with constrained right-of-way's or with minimal vertical and/or horizontal clearances.

It has been observed that the bridge performance is highly affected by the weather (Nemry and Demirel 2012[1]). In the design stage, assumptions about the range of temperatures, precipitation level, and wind speed are incorporated from historical climate data. Thus, bridges could be greatly impacted by the climate changes, mainly through increase of average temperatures, increases in different types of climate extremes such as hot/cold days, intense precipitation events and development of flash floods, and raising sea levels coupled with storm surges and hurricanes. The on-going effects of the climate changes are expected to have an impact on bridges through increasing rates of deterioration and the impact of extreme whether events (Wang et al. 2010[2]). Elements of aging bridge infrastructure are subjected to service loads and they are affected by progressive environmental loads that results in a successive reduction of their structural capacity. If an over loading situation is expected over the bridge lifetime (for example an ultimate load), then the collapse of a critical structural element is more probable. Saetta et al. 1999 [3] indicated that strength and ductility of aging RC structures are very important aspects of the structural behavior at ultimate load as they are highly related to their durability. The long term structural performance of bridge elements, their instantaneous load-bearing capacity, and their mode of failure are all dependent on the degradation of both, the concrete and reinforcing steel.

One of the expected changes is an increase in annual temperatures; also, changes are expected in the ranges of maximum and minimum temperatures. In the short-term, no major impact on the structural performance of the bridges is expected due to temperature changes. However, in the long-term, temperature changes will result in extreme stresses on the bridges due to the thermal expansions and contractions. On the other hand, with global increase of ambient temperature it is observed that bridge columns are more frequently affected by scour events as a result of early melting of snow and glaciers due to high winter temperatures will result in higher flow rates and more turbulent flows. This will require development of regional maximum/minimum temperatures as well as seasonal and even daily temperature variations. In this context, the overall bridge deformations due to significant changes in the thermal stresses are induced due to the variations either in the temperature gradient over the cross-section or high changes in the overall extension due to uniform temperature (ambient temperature). Such thermal loading influences the design of the bridge structural elements and joints. Failure to allow effects like repeated cycles of heating and cooling may magnify the distress in various parts of the bridge (Tong et al. 2000[4]). For instance; the elevated ambient temperature could severely damage the expansion joints and affects its functionality (Chang and Lee 2001[5]); also, the bridge structural load capacity could be seriously decreased due to the climatic driven accelerated deterioration (Bastidas-Arteaga et al. 2013[6]). Exposure of structural elements to extreme environmental conditions could initiate, accelerate, and propagate reinforcement corrosion. Hence, the structural performance and stability of these damaged bridges could severely deteriorate.

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 escalation in frequency and intensity of extreme weather events are now obvious. It is widely believed that future climate changes may lead to very high climatic stress on infrastructure including loads, 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 and resiliency 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 frame bridge resiliency. When the bridge is damaged or collapsed due to accelerated deterioration with the changing climate and/or extreme climate event, the resiliency enhancement should be provided in terms of minimum recovery time, higher target performance, using rapid strength and ductility enhancement approaches. 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 frame concrete bridge.

SIMPLIFIED NONLINEAR ANALYSIS APPROACH FOR EVALUATING STRUCTURAL PERFORMANCE OF AGING FRAME BRIDGES

In order to simulate the failure mechanisms and structural performance of aged frame bridge element, it is essential to capture all possible stages of damages, and the resulting changes in structural performance in terms of ultimate capacity and serviceability at each damage state. The nonlinear finite element model, FEM, developed by Mohammed 2014[7] has been used here. The model integrates a nonlinear sectional analysis and an element structural analysis into one consistent modeling approach that is capable to evaluate the structural performance of damaged frame bridge. The nonlinear sectional analysis simulate the element sectional rigidities and the element structural analysis evaluates the structural performance and residual capacities of beam-columns. The bridge is considered to be subjected to service or extreme climatic and service loads combined with reinforcement corrosion.

MODELLING DIFFERENT SCENARIOS FOR AGING FRAME BRIDGES RESILIENCE

In a typical rigid frame bridge, the superstructure is rigidly connected to the substructure in a frame structural system. The integration between the superstructure and the substructure results in a continuity of the bridge stiffness and effective mass, which enables immense structural resistance to the static and dynamic loads applied on the bridge. Recently, more slender and elegant frame bridges are built using reinforced concrete deck slab compositely connected to either multiple steel frames, or multiple prestressed reinforced concrete frames- precast or cast in site. On the other hand, a resilient infrastructure system can be defined as a system that provides adequate performance against cumulative damage and extreme climatic stresses at an acceptable cost over its life cycle (Lounis and McAllister 2016 [8]). 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 [9]). Following excessive an extreme climate event, there is need to restore the structural performance of the frame bridge system, for instance, to a prevent level or even to a higher performance level.

Based on the type of frame bridge structure, different scenarios for the resiliency of the bridge system when subjected to extreme climate events are modeled in this study. Figure 1 shows a conceptual presentation of these scenarios. The blue line (sold and dotted) represent the performance line of the bridge structural system over its life time when no sudden-significant drop in performance has taken place. If a sudden drop of the bridge structural performance happens due to an extreme climate event (the vertical red sold line in Figure 1), then the bridge load capacity will drop suddenly. In this study, three scenarios for the bridge damage are assumed: (i) The bridge deck slab is partially or fully damaged and only one exterior frame of the frame bridge is partially damaged (this damage is assumed to reduce the bridge capacity by up to 50%); (ii) The bridge deck is largely damaged with the damage of more than half of the bridge frames which leave only one lane of the bridge functional (this damage is assumed to reduce the bridge capacity by up to 75%); and (iii) The bridge frames and deck slab are fully damaged and/or collapsed (this damage is assumed to reduce the bridge capacity by 100%).

The time required for each rehabilitation/ strengthening approach that enable the bridge to recover its full design capacity or a higher load capacity present the effectiveness of the bridge resiliency. The brown line in Figure 1 present the performance of the bridge over its service life after performance recovery to the design load capacity. The green line in Figure 1 present the performance of the bridge over its service life after performance recovery to the required load capacity to avoid losing the bridge with higher magnitude and frequency of the extreme climate events. The inclined brown arrows present the recovery of bridge performance to the original design level from the three assumed damage scenarios mentioned earlier. The slop of these arrows present the recovery speed or the effectiveness of the bridge resilience. The inclined green arrows (sold or dotted) present the recovery of bridge performance to the required performance level from the three assumed damage scenarios shown in Figure 1 by different colors. The sold green arrows having higher of sharper slops than the slopes of the dotted green lines, which means the sold green arrows present faster recovery time than the dotted green arrows. The accelerated bridge construction is apparently providing the highest possible recovery time (the sold green arrows) versus classical in-site construction approach (the dotted green lines).

Figure 2 shows the framework for resilient frame bridge. Two major accelerated bridge construction approaches are the base for reducing the bridge recovery time, which are Precast Prestressed Accelerated Manufacturing and Accelerated In-Site Construction. Both approaches, when integrated in a frame bridge recovery process, will lead to an enhanced resiliency in terms of: (i) load capacity enhancement; (ii) bridge ductility improvement; (iii) shorten recovery time where rapid structural strengthening techniques are to be used.

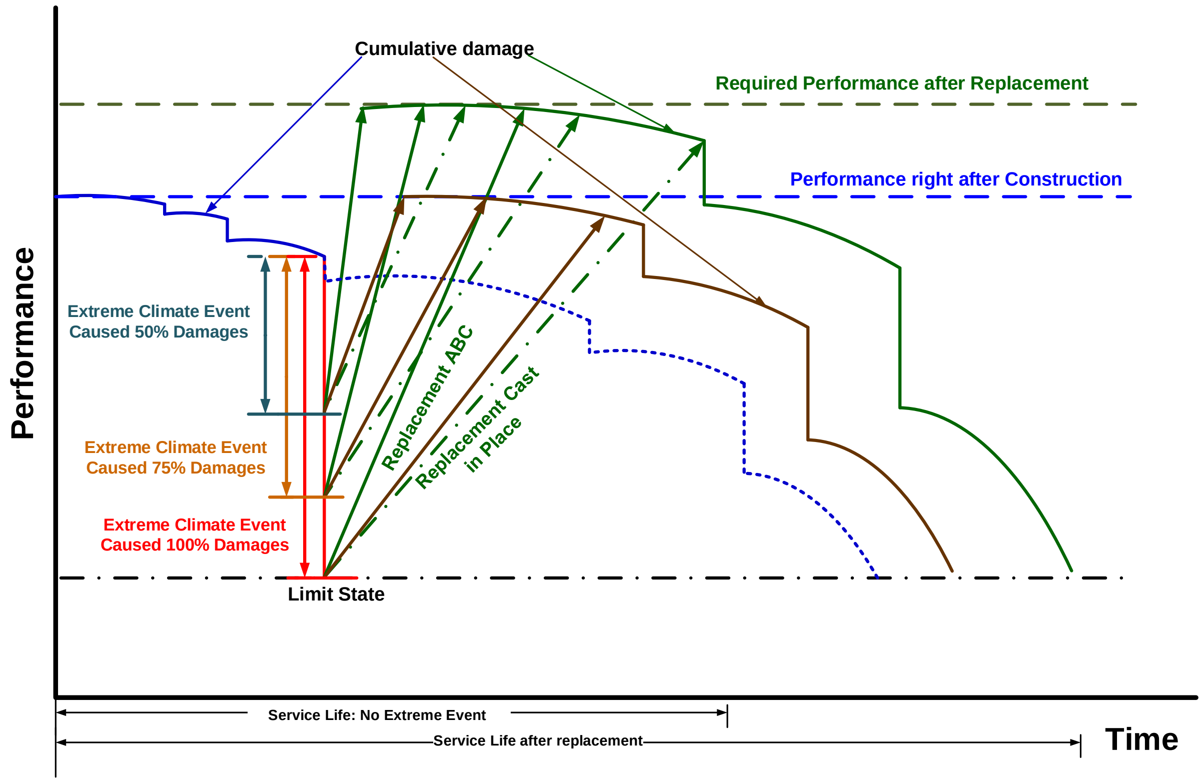

Figure 1: Schematic representation of resilient structural frame bridge system

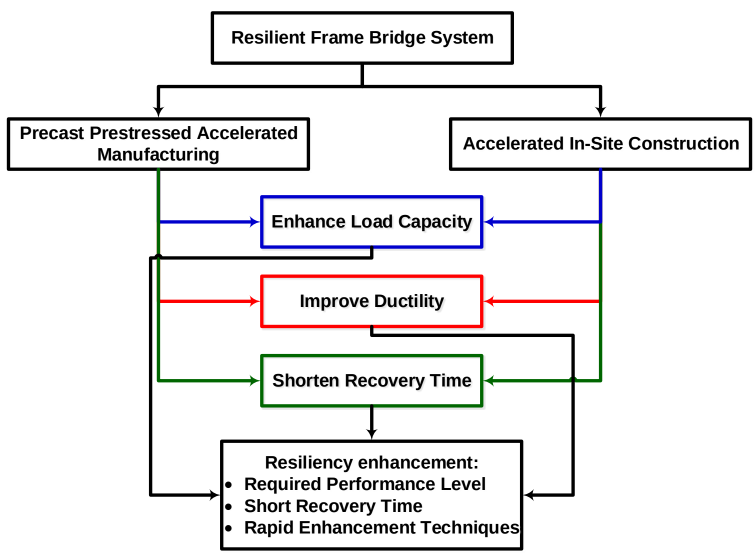

Figure 2: Framework for resilient Frame Bridges

CASE STUDY

In this case study, a precast-prestressed frame bridge is modelled as a structural system subjected to static and dynamic loads including moving trucks. The bridge consists of five precast-prestressed frames (see Figures 3 (a) and (b)); each frame consists of five elements rigidly connected and post tensioned: (i) two inclined columns; (ii) two overhang girders; and (iii) a central girder. The bridge covers a total span of 100 m with central span of 68 m at the bottom of the columns and 58 m at the top of the columns, two "over-hanged" side spans of 20 m each with a total 10 m height of the bridge. The frame section is variable in depth as shown (not to scale) in Figure 3 (a) with depth variation between 1.4 m to 2.0 m. The inclined column is rigidly connected to the foundation, while the "over-hanged" side spans are supported to the side abatements by rollers. The spacing between frames is 2.5 m from center to center, where the five frames are compositely integrated with reinforced concrete deck slab of 0.225 m thickness (see Figure 3 (b)). It is impotent to mention that only preliminary design of the bridge is conducted as the detailed optimized design is out of the scope of this study. The focus of this study is on the evaluation of the bridge residual capacity in different levels of damage and time required to the bridge recovery to its structural performance after the construction or the required structural performance as mentioned earlier.

In this study, three scenarios for the bridge damage are assumed: (i) The bridge deck slab is partially or fully damaged and only one exterior frame of the frame bridge is partially damaged (this damage is assumed to reduce the bridge capacity by up to 50%); (ii) The bridge deck is largely damaged with the damage of more than half of the bridge frames which leave only one lane of the bridge functional (this damage is assumed to reduce the bridge capacity by up to 75%); and (iii) The bridge frames and deck slab are fully damaged and/or collapsed (this damage is assumed to reduce the bridge capacity by 100%).

As shown in Figure 4, the bridge has its full capacity as constructed when affected by the climate event (80,000kN.m, blue line). If the bridge superstructure partially damaged (partial damage of deck slab), the bridge capacity is dropped down up to 60,500kN.m (which is almost 80% of the original structural capacity; purple line). If more than two frames of the superstructure significantly damaged, the bridge capacity would drop to 60% of its original capacity (see Figure 4). Due to the partial failure, the bridge width is decreased which would lead to close one or two lanes of the traffic (if the remaining part of the bridge is approved to be safe). Figure 4 shows an extreme climate event that would cause a full (or 100%) damage, where the bridge is totally losing its capacity (red line). In this case, the bridge replacement is mandatory considering the required performance to avoid similar failure in future.

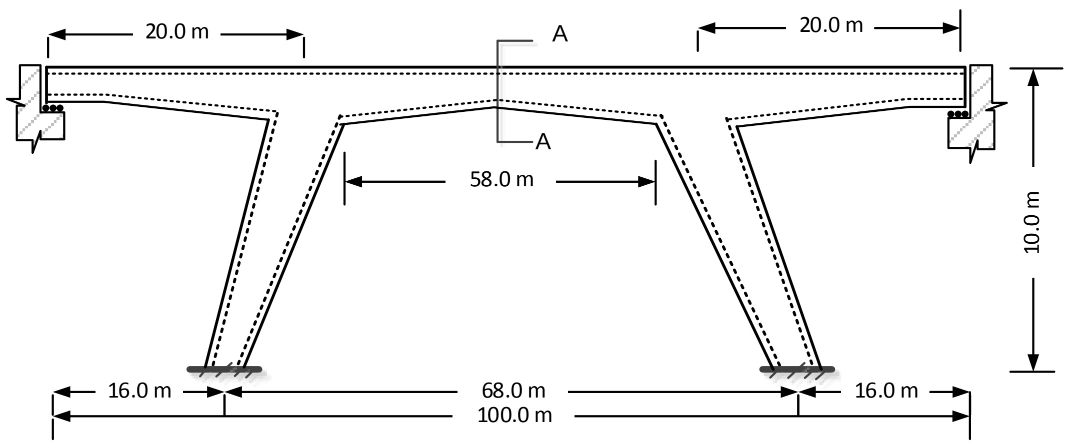

Figure 3 (a) Precast Prestressed Concrete Frame Bridge

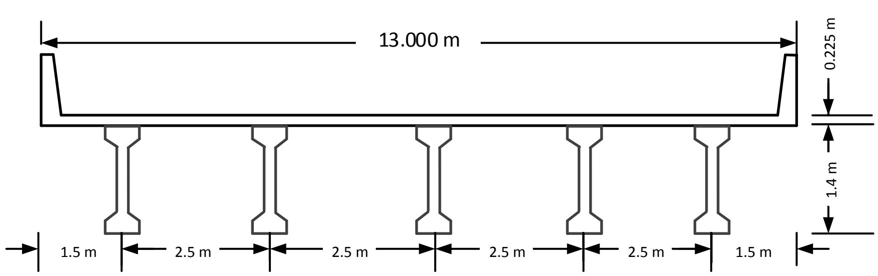

Figure 3 (b) Section A-A

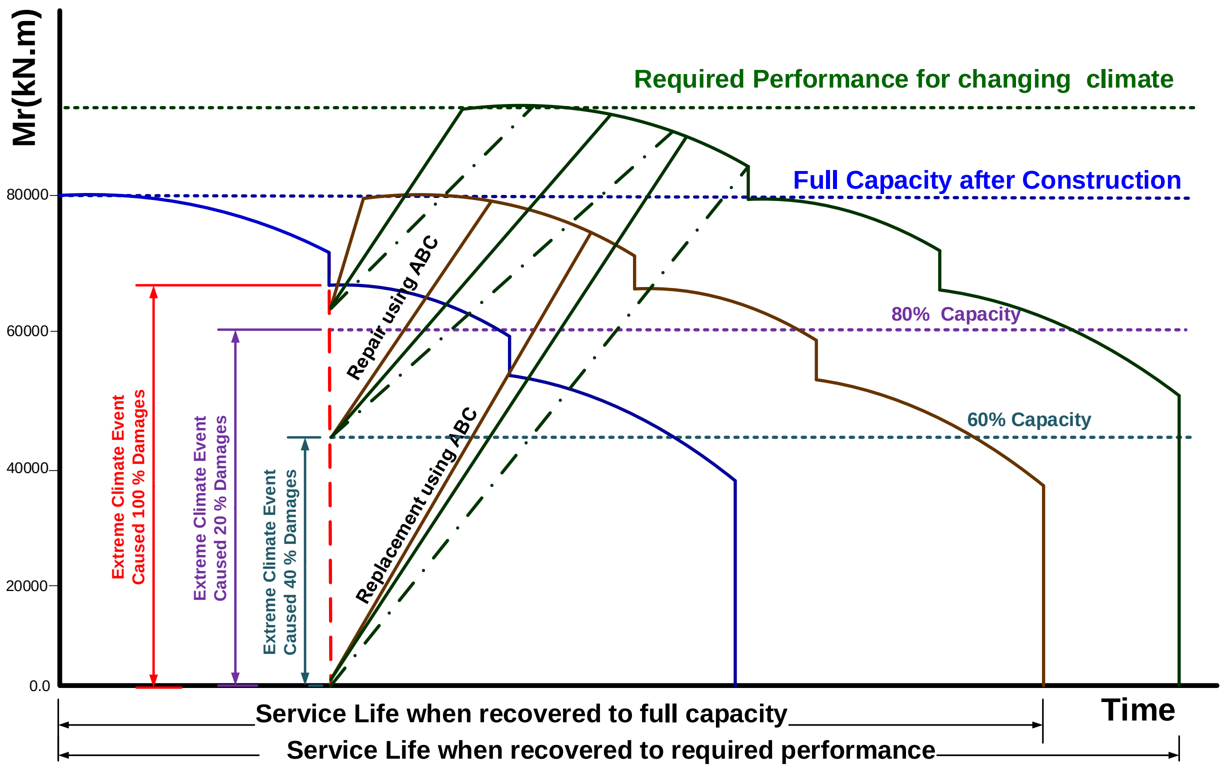

Figure 4 Frame bridge system resilience with ABC versus traditional rehabilitation for different damage levels due to extreme climate events

ENHANCEMENT AGING FRAME BRIDGES RESILIENCY USING ACCELERATED BRIDGE CONSTRUCTION

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. In the case study, the three scenarios for the bridge damage are assumed: (i) The bridge deck slab is partially damaged (this damage is assumed to reduce the bridge current structural capacity by 20%); (ii) The bridge deck is partially damaged with the damage of one the bridge exterior frames (this damage is assumed to reduce the bridge current capacity by 40%); and (iii) The bridge frames and deck slab are fully damaged and/or collapsed (this damage is assumed to reduce the bridge capacity by 100%).

The recovery plan and the required capacity after the climate extreme event is to 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 where their recovery should be immediate as 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 of the frame bridge: (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.

The inclined brown arrows present the recovery of bridge performance to the original design level from the three assumed damage scenarios mentioned earlier. The slop of these arrows present the recovery speed or the effectiveness of the bridge resilience. The inclined green arrows (sold or dotted) present the recovery of bridge performance to the required performance level from the three assumed damage scenarios shown in Figure 4 by different colors. The sold green arrows having higher of sharper slops than the slopes of the dotted green lines, which means the sold green arrows present faster recovery time than the dotted green arrows. The accelerated bridge construction is apparently providing the highest possible recovery time (the sold green arrows) versus classical in-site construction approach (the dotted green lines).

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[10]).

CONCLUSIONS

The recovery plan and the required capacity after the climate extreme event is to be decided by infrastructure owners based on the bridge importance to the transportation network. After a major disaster, bridges are suggested to be categorized into three types: (i) very important bridges where their recovery should be immediate (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 affected by the level of damage the bridge experience, the required performance of the bridge after an extreme event, and the rehabilitation or reconstruction approach. Based on the bridge importance and the required load capacity, two performance levels are the target of the performance recovery plan of a frame bridge: recovery of the bridge structural performance to the original or to a higher performance level. The recovery speed presents the effectiveness of the bridge resilience. The accelerated bridge construction is providing the highest possible recovery time versus classical in-site construction approach. 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 frame bridges.

REFERENCES

[1] Nemry. F., and Demirel. H. 2012. “Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures.” European Commission, Joint Research Centre (JRC), Institute for Prospective Technological Studies (IPTS), PP 93.

[2] Wang, X., Nguyen, M., Stewart, M. G., Syme, M., and Leitch, A. 2010. “Analysis of Climate Change Impacts on the Deterioration of Concrete Infrastructure Part 3: Case Studies of Concrete Deterioration and Adaptation.” CSIRO, Canberra. ISBN 9780643103672.

[3] Saetta, Anne, Scotta, Roberto, and Vitaliani, Renato.1999. “Coupled environmental-mechanical damage model of RC structure”. J. Eng. Mech. 125(8); 930-940.

[4] Tong, M., Tham. L., Au. F., and Lee. P. 2001. “Numerical modelling for temperature distribution in steel.” Computer & structures; 6(30). PP 583-593.

[5] Chang. L., and Lee. Y. 2001. “Evaluation and policy for bridge deck expansion joints.” Final report: FHWA/IN/JTRP-2000/1; February.

[6] Bastidas-Arteaga, E., Schoefs, F., G. Stewart, M., Wang, X. 2013. “Influence of Global Warming on Durability of Corroding RC Structures: A Probabilistic Approach”, Engineering Structures, Elsevier, 51, pp.259-266.

[7] Mohammed, A. 2014. “Semi-quantitative assessment frame-work for corrosion damaged slab-on-girder bridge columns using simplified finite element analysis”. PhD. Thesis, Dep. Of Civil Engineering, University of Ottawa, Ottawa, Canada.

[8] Lounis, Z. and McAllister, T. 2016. “Risk-Based Decision-Making for Sustainable and Resilient” Infrastructure Systems. Journal of Structural Engineering. ASCE, 142(9). F4016005.

[9] Biondini,F., Camnasio, E., and Titi, A., 2015. “Seismic resilience of concrete structures under corrosion”. Earthquake Engineering Structural Dynamics, (44).
[10] Palermo, A., and Mashal, M., 2012. “Accelerated bridge construction (ABC) and seismic damage resistant technology: a new Zealand challenge”. Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 45, No. 3.