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Evaluation of the structural condition of the Reinforced Concrete (RC) bridge on the Hakim highway-Kan river intersection and presentation of a proposed model for its maintenance and seismic retrofit

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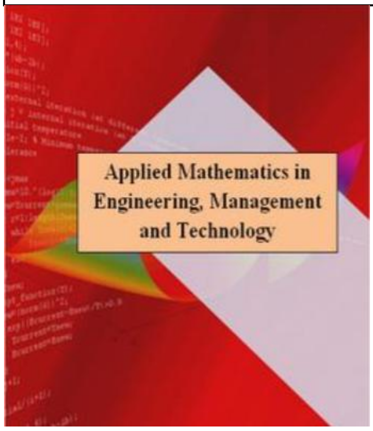

Abstract

Bridges are among those types of structures which their serviceability under service loads and after earthquakes is extremely important. Tehran is located in a region with a high risk of seismic activity, so it seems necessary to conduct visual inspection and field observations throughout this city in order to make technical evaluation and assess the structural and non-structural weaknesses and defects in vital urban structures such as the bridges. On this basis, this study assessed the structural condition and non-structural weaknesses of the RC bridge on the Hakim-Kan river intersection in Tehran, and presented basic strategies for its maintenance and seismic retrofit.

Keywords: Structural condition, Hakim-Kan river intersection bridge, Seismic retrofit

1. Introduction

In recent years, economic considerations have given the retrofit of existing infrastructures a priority over rebuilding them [1]. Bridges are one of the most important elements of urban transport system, and provide the connection between different urban areas. So strengthening, maintenance, and seismic retrofit of these structures is very important. Researchers have concluded that regular and periodic inspections of bridges, particularly RC bridges, have an important role in increasing the life span and non-stop serviceability of these structures. The history of vulnerability assessment of bridges goes back to four decades ago when it was conducted to assess the cost of rebuilding the bridge based on the severity of the damage to the members [2, 3]. In general, evaluation and structural retrofit of a bridge require three basic steps including: 1- visual inspection and assessment of the structure, 2- detection or prediction of bridge's damaged components, and 3- planning and selecting the best and most efficient option for the seismic retrofit and maintenance [5].

Financial losses and loss of life caused by the destruction of bridges for various reasons such as applying unconventional loads, geometric changes of the pier, low quality of construction and weakness of design and construction laws and regulations, make focusing on the maintenance of bridges a vital objective [5, 6]. In this study, we attempted to briefly assess the structural condition, weaknesses, and damages of the RC bridge on the Hakim-Kan river intersection in Tehran, using mainly qualitative and occasionally quantitative evaluations. According to the conducted studies, this bridge is located in a high seismic risk region, and its probability of failure and collapse has been estimated to be very high. Therefore, it is necessary to pay attention to the structural condition and seismic retrofit of this bridge and carefully reassess the uninterrupted serviceability of this bridge after an earthquake. In the following sections, after initial assessment of the bridge, the model used for its inspection, repair, maintenance and seismic retrofit will be introduced, and the bridge's maintenance and retrofit index will be evaluated using the mentioned model.

2- The studied bridge

The bridge of Hakim-Kan river intersection is a 6 span RC bridge with concrete I-shaped girders and in situ slabs. The bridge deck is composed of two individual parts which are separated along the length of the bridge and situated on Neoprene bearing pads (Figure 1). In terms of construction materials, this bridge is in the category of RC bridges with I-shaped girders and in situ slabs; in terms of span length, since its span length is 32 meters, it can be considered as a medium span bridge (between 8 and 50 meters); in terms of structural system, this bridge is in the category of beam-slab RC bridges; and in terms of function, this bridge is within the category of Viaducts [5].

Figure 1: a general view of Hakim-Kan river bridge

3. The field surveys and reports on current condition of the bridge

3.1. Condition of the superstructure

3.1.1. Deck

The deck of this bridge consists of two separate parts with the same geometrical characteristics and a width of 16 meters; each part has 3 lanes and is constructed by in-situ slabs. This bridge has a drainage system for the collection of surface water, but its condition is not satisfactory. The major problem that can be seen in the deck slab of this bridge is the presence of efflorescence below the deck and around the drainage pipes. This efflorescence indicates poor insulation of the deck surface and failure of its drainage system.

2.1.2. Girders and transverse diaphragms

In this bridge, girders are connected together by transverse diaphragms and are main components responsible for transferring the load from the main deck to the column caps and to the columns, but they have efflorescence in some areas that must be examined more accurately. The important issue related to the girders of the bridge is the high probability of slip between girders and their bearings because of the two main reasons: 1- insufficient width of the seat, to support girders' longitudinal and transvers displacement, and 2- rotation of piers. The transverse diaphragms are built on the bearings and in the center of each span of the bridge to ensure integrated function of the structure in the transverse direction. The height of these diaphragms is approximately equal to the height of the girders, and there are some large holes in their center for the passage of utility pipes that in some parts lead them through channels embedded in those diaphragms. It should be mentioned that these holes reduce the stiffness and strength of these elements that must act like a fuse. Also in some sections of transverse diaphragms the concrete which must cover the rebar is destroyed, and severe degradation of concrete has revealed plain (smooth) longitudinal reinforcement bars along the diaphragms and some of these bars are rusted and also some pipes appear to be inside the diaphragms' holes that should be examined at a later stage. The mentioned condition of bars in that section can later get combined with corrosion caused by oxidation and moisture (which is not easily detectable) and may cause honeycombing phenomenon in concrete and ultimately transverse cracking in the deck, girders and diaphragms.

3.2. Condition of the substructure

3.2.1. Bearings

This bridge has elastomeric (Neoprene) bearings which connect I-shaped concrete girders to column caps. It can be said that they are in good condition, and there are no damages or unusual displacement in this regard.

3.2.2. Abutments

There is a spill-through abutment at each end of this bridge that consists of a deep beam and a number of columns. Position of the abutment's columns is just below the bridge girders, and since abutment is not constructed as a wall, soil behind the abutment has moved through and has covered around the piers. Overall, this bridge's abutments are in good conditions and have no major structural problems. In some sections there is some efflorescence that must be examined. The position of deep beam which acts as abutment on top of the piers has allowed some soil from the other side to move under the bridge which has no effect on the structural performance of the bridge.

3.2.3. Column caps and middle piers

Concrete column caps support the bridge deck in the spans between abutments and can be considered as the seat for the girders. In this bridge, the width of the seat is small and does not match the design capacity of the piers which can lead to transvers dislocation of superstructure and impose additional forces to the piers as a result of contact with the piers and in the event of an earthquake with severe shaking may also lead to severe structural damage. In addition, in the column caps adjacent to the abutment, part of the concrete column caps is dislodged, but there is no cracking and protrusions on piers. In some upper parts of the piers, there are some large holes to allow passage for utility pipes, but no utility pipe has passed through these holes. It seems that these holes are not in the structure's original design and since these holes have been created near the column caps, they will have negative effect on the mentioned piers in terms of withstanding the forces of an earthquake. In the event of an earthquake and resulting vibrations, two ends of each column will be the position of formation of plastic joints, so in the next stage of studies this issue must be considered in the modeling.

3.2.4 Foundation

This bridge's complete structural plans were not available, but the field observations showed that in the transversal direction, foundations are in the form of strip. It is also possible to guess that overload and poor design of this bridge's foundations may in the near future cause flexural and shear cracks and unbalanced subsidence in the foundations.

4. Technical assessment of bridge's structural weaknesses and damages

Field surveys conducted on the studied bridge determined that its deck and piers are in almost good conditions, but abutments and foundations (due to their unavailability) should be examined through sonic probing and more accurate visual inspection. Given the high length of the bridge, it is recommended to carefully measure its dimensions and enter them into related seismic maps. Visual inspection and available plans showed that bridge's guardrail system has some shortcomings, and the presence of large holes in piers especially near the column caps can cause structural problems for the bridge. Soil has irregularly filled around some of the piers and this has caused them to have different stiffness; this will have significant effect on the manner of transfer and distribution of load between the members, which is probably an issue that is not in the capacity of elements' design. The presence of holes in transvers diaphragms that have been embedded for the passage of utility pipes has reduced their stiffness, and this issue highly reduce transverse load bearing capacity of the bridge structure in earthquake, and this is exactly why detailed seismic studies should be conducted on this bridge.

5. Assessment of the bridge maintenance and seismic retrofit system

Limited resources for maintenance and retrofit of RC bridges and also various challenges caused by current condition of urban bridges have created an need for a convenient and efficient method for prioritization of bridges for maintenance. Appropriate models for this prioritization require an appropriate database for processing of data [7]. Therefore, providing a decision support system for prioritization of maintenance for RC bridges is essential in allocating maintenance resources in a time period. In these systems, prioritization models are based on predetermined important criteria and also an accurate database. In the following section, the model proposed by "Valenzuela" is used for the prioritization of criteria for the maintenance and retrofit of the studied bridge [8].

This model is based on an index which is called integrated Bridge Index (IBI) and is used for the prioritization of bridge maintenance and retrofit and for proposing strategic suggestions at network level. This model is created through the development of a tool which is easy to use, requires a small amount of data and uses the characteristics of the road network [8].

5.1. Integrated Bridge Index

Integrated bridge index can be estimated by equation (1) which uses parameters such as strategic importance, hydraulic vulnerability, seismic risk, and bridge condition. The minimum value that integrated bridge index (IBI) can take is 1 which would indicate that bridge is in critical condition and the maximum value that this index can take is 10 which would indicate that bridge is in a very good condition. The bridge can be prioritized for maintenance with regard to value of this equation.

(1) $IBI = -1.411 + 1.299BCI + 0.754HV + 0.458SR - 0.387SI$

5.1.1. Strategic Importance Index (SI)

The "Strategic Importance" represents the importance of the bridge in the road network. Bridges which are located in road networks without alternatives routes, have high traffic, and are located in farm areas, have higher strategic relevance for the transport systems. The value of this index can be obtained through the following equation:

(2)

$SI = 0.261EA + 0.206T + 0.193SEE + 0.093W + 0.133L + 0.114R$

In the above equation, EA represents the alternative route index ,T is the average annual daily traffic index, W and L are the bridge width and length indexes, SEE represents social and economic environment index, and R is the load restriction index. The tables below should be used to determine the above parameters.

Table 1: Bridge rating based on alternative routes–EA [8]

Type of detour	Rating	Description
Parallel structure	1	There is a structure nearby the bridge that permits traffic flow with low disruptions and delays
Parallel structure or road	2	There is a structure nearby the bridge that permits traffic flow with congestion. There are roads with similar standard as alternatives. The travel distance is similar. The time of travel and costs of using the road do not change.
Long detour	3	Alternative roads increase the time of travel and costs of using the road. Minor congestion is observed on the bridge.
Very long detour	4	The alternative road adds 10 km or more to travel distance. The standard of the alternative route is lower than the main route. High probability of congestion on the bridge.
Without detours	5	There are no alternative routes.

Table 2: Bridge rating based on Annual Average Daily Traffic (AADT) –T [8]

Traffic level	**Rating**
Low (AADT < 2000)	1
Medium (1200 < AADT < 3000)	3
High (AADT> 3000)	5

Table 3: Bridge rating based on the zone and the economic activities supported by the road – SEE [8]

Zones of the country	**Rating**	**Zones of the country**
North	5	**Economic activities**
	3	Mining
	1	Farming and fishery
Central	5	Other
	3	Industrial, Farming
	1	Mining and fishery
South	5	Other
	3	Farming, Forestry
	1	Livestock, aquaculture

Table 4: Bridge rating based on bridge deck width – W [8]

Qualification of width	**Ratin g**	**Description**
Unsatisfactory	1	The bridge has one or more lanes with constant problems in terrific passage; very narrow deck
Satisfactory	3	Two-lane bridge deck; narrow lanes produce passage restriction for heavy trucks.
Very satisfactory	5	Two or more lanes bridge deck; There are no restrictions on the passage.

Table 5: Bridge rating based on bridge deck length – L [8]

Long range (m)	**Rating**	**Type of the bridge**
≤ 30	1	Very short
$30 < L \leq 50$	2	Short
$50 < L \leq 150$	3	Regular
$150 < L \leq 300$	4	Long
L>300	5	Very long

Table 6: Bridge rating based on load restriction – R [8]

Type of restriction	Rating	Description
Highly restricted	1	The passage of heavy trucks is forbidden; Restricted passage for light vehicles.
Medium restrictions	3	The passage of heavy trucks is forbidden; There is no restriction on the passage of other vehicles.
No restriction	5	There is no restriction on the passage of any type of vehicle.

5.1.2. Hydraulic vulnerability index (HV)

This index can be obtained using the following table where the visual inspections are the main input. This type of visual inspection includes assessing the condition of river bed, river banks, and flow condition. In this method, the assessment of river flow condition is based on the probability of flood damaging the bridge surface or the bridge structure.

Table 7: Bridge rating based on Hydraulic vulnerability – HV [8]

Rating	Vulnerability level description	
5	None	There is no probability of failure because of the river forces.
4	Low	It is highly unlikely that the bridge and its complementary works fail as a result of floods and/or scour.
3	Medium	It is likely that the bridge and its complementary works fail as a result of floods and/or scour
2	High	It is very likely that the bridge and its complementary works fail as a result of floods and/or scour
1	Very high	The bridge and its complementary works are in imminent danger of failure

5.1.3. Seismic Risk index (SR)

In this model, The SR index can be obtained according to the damage level modeled in each structure; the definitions of these levels are presented in the related table. The exact extent of the damage level can be determined through using Fisher's numerical model which itself uses ground acceleration and structural response.

Table 8: Bridge rating based on Seismic Risk – SR [8]

Rating		**Damage level (%)**	**SR level description**
5	None	0 - 20	There is no likelihood of failure by seismic loads
4	Low	20 - 40	The bridge failure as a result of earthquakes is highly unlikely
3	Medium	40 - 60	It is likely that the bridge will fail under seismic loads
2	High	60 - 80	It is very likely that the bridge will fail under seismic loads
1	Very high	80 - 100	The bridge is in imminent danger of failure due to earthquakes

5.1.4. Bridge Condition Index (BCI)

Bridge Condition Index is a quantitative index that indicates the structure's damage level based on the visual inspections. BCI can be obtained through the following equation.
(3)

$$BCI = \sum_{i=1}^{n} w_i m_i ECI_i \Big/ \sum_{i=1}^{n} w_i m_i$$

In the above equation, ECI_i represents the element condition index for the element "i", w_i is the weight of the element "i" with respect to the whole structure, and m_i is the material factor of each element.
Visual inspections are necessary in the process of obtaining the BCI and following notes must be considered in this process [8]:

- Calculation of element condition index for each element is carried out based on visual inspection and rating of the element.
- When a bridge has several elements of the same type, for example, several piers, the one that is in worst condition must be selected as the representative of that element in the index.
- The element weight is defined for typical elements of each type of bridge structure. The weights range between 1 and 5. The primary beam and piers for example have a weight of 5, but the road signs have a weight of 1.
- Each weight must be multiplied by the material factor m_i. this factor represents the material vulnerability, which ranges between 1 (prestressed concrete) and 4 (timber).

It should be stated that BCI parameter for the studied bridge was obtained as 1.9.
After the field surveys and visual inspections of the bridge on Hakim highway -Kan river intersection, the value of each parameter related to Integrated bridge index was identified, and then they were highlighted in the corresponding tables. According to equation (1), and based on our calculations, the integrated bridge index of the studied bridge is 2.5. This value shows that this bridge is in semi-critical condition in terms of its serviceability and function, and also indicates that small factors such as flooding, high traffic load, passage of time, and most importantly earthquake (even a small one), can push this bridge into critical condition and jeopardize the role of this bridge as a vital component in the road network. Therefore, the development of necessary programs for maintenance and seismic retrofit of this bridge should be placed on the agenda as soon as possible.

6. Conclusion

Bridges as an important part of infrastructures and vital networks of a country, play a significant role in the economic development and progress of that country, and their destruction -regardless of causing factors- can have disastrous results for the society; therefore, it is essential to provide the necessary measures for repair, strengthening and seismic retrofit of bridges before structural failure due to unconventional loads such as earthquake. In this study, we assessed the structural condition, weaknesses, and damages of the RC bridge on the Hakim-Kan river intersection in Tehran, using mainly qualitative and occasionally quantitative evaluations. As a result, the main reasons behind the structural weaknesses and vulnerabilities of this bridge include: 1- the lack of sufficient and decisive technical inspections on the structural elements of the bridge, 2- the partial absence of structural plans, technical documents and as-built plans of this bridge, 3- inadequate quality of construction and lack of strict monitoring and inspection during the construction of superstructure and substructure, 4- the excessive use of predesigned typical elements in the designs and lack of attention to the site of the structure, and 5- using the old standards and regulations for the design of structural and non-structural elements. This paper is presented to provide the appropriate conditions for the minimization of the risks to life and property caused by the earthquake, and the development and deployment of a comprehensive system of quality control and maintenance and retrofit management based on the suggested maintenance and retrofit model. For this purpose, the suggested model which is called “Integrated Bridge Index” was used to assess the priority of repair, maintenance and seismic retrofit of the studied bridge. The results showed that this bridge is in semi-critical condition and small factors such as flooding, high traffic load, passage of time, and most importantly earthquake (even a small one), can push this bridge into critical condition and jeopardize the role of this bridge as a vital component in the road network. Therefore, the development of necessary programs for repair, maintenance and seismic retrofit of this bridge should be placed on the agenda as soon as possible.

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