Seismic Performance of Composite Simply Supported Bridge Decks during Real Earthquake

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Abstract. This study investigates the overall response of traditional bridge decks in Iraq under real earthquake excitation already happened in the area. The bridge deck under investigation is of Al Bathah overpass expressway located in the south of Iraq at Al Nasiriya city. Al Bathah Bridge deck is a composite simply supported consist of seven built-up steel girders and reinforced concrete slab. Three-dimensional finite element models of composite simply supported bridge deck was created using CSI Bridge and ABAQUS software. Time history analysis conducted using the Halabja earthquake hit the Iraq-Iran border on 12 Nov. 2017. The finding of this study revealed that the typical bridge deck in Iraq will fail to withstand the transverse earthquake excitation under intensity already happened. The connection epoxy layers between the elastomeric bearing pads and girders will fail due to the excessive transverse displacement at bearings. Consequently, the girders slip from their position and the deck will fail.

1. Introduction
Many existing bridges and overpasses made of simple composite spans are designed to withstand loads of gravity and vehicles plus factors taken from old building codes to resist earthquakes, especially in the middle and south of Iraq. No account was found for significant seismic activity. In the past, the earthquake force transmitted by the superstructure was assumed to be below the stage leading to a critical failure of the superstructure parts to behave inelastically. Recent moderate to high earthquakes have shown that this theory is ineffective and deformation has been reported in the superstructure of the steel girder bridge [Todd et al. in 1994; Shinozuka in 1995; Bruneau et al. in 1996]. Severe damage was also noted in the superstructure due to the overload of end cross frames and diaphragms and bearing failures. There is much research on the bridge substructure's seismic performance in terms of analysis and design but studies on the bridge superstructure and its response to the earthquake are limited based on the premise that the bridge deck's behavior appears to be rigid. Detailed investigation is, therefore, necessary to check these superstructures if they can withstand real-time earthquakes occurring in the area. Many large earthquakes have struck Iraq and the surrounding area with intensities greater than 4 magnitude (Mw) over the past ten years. Therefore, the behavior caused by earthquakes in existing bridge superstructures, particularly after the November 2017 Halabja earthquake with Mw 7.3, has become important to analyze. Zahrai and Bruneau, in 1998 investigate the effect of frame diaphragms on the seismic performance of slab on girder steel bridge into part the first one with diaphragms and the second one without diaphragms. It was shown that to make the superstructure act as a unit in elastic limits, a small diaphragm stiffness was needed. However, a dramatic shift in seismic behavior occurred when the end diaphragm was ruptured. Furthermore, it has
been shown that the intermediate diaphragms do not significantly improve slab seismic efficiency on girder bridges. Itani et al., in 2004 discussed the behavior of the steel girder bridge superstructure in recent earthquakes such as Kobe, Petrolia, and Northridge. Furthermore, the findings of recent experimental and theoretical studies on steel girder bridge configurations are discussed. It showed that shear connectors are necessary to transfer and distribute lateral force to the cross frame. However, these investigations showed that the cross frame can be used as a ductile component to dissipate the earthquake input energy. In this paper the seismic response of composite simply supported bridge deck was investigated under a truly recorded earthquake applied in the transverse direction of bridge (perpendicular to the bridge main axis) using two commercial software, CSI Bridge and ABAQUS software.

2. Case Study

Al Bathah overpass expressway is a case study of this work which located in Al Nasiriya city in the south of Iraq. The composite simply supported bridge deck of the bridge under inquiry consist of two main components; the built-up steel girders and reinforced concrete slab. Shear stud connectors used to connect the reinforced concrete slab with steel girders on the top flange. These girders rest on elastomeric pads at the end of each girder and the pedestal concrete pads located under the elastomeric bearing pads used to support these bearing. The elastomeric bearing pads connected actually by epoxy cohesive layers only with steel girder on the top face and with the pedestal on the bottom face with no bolts to fix it at the connection point, it is a critical part in the bridge deck. Five sets of cross-frame diaphragms used to connect the girders, two sets at the ends and three sets in the middle. Figure 1 shows Al Bathah bridge deck configurations which were used in this study. The material properties are shown in Table 1.

![Figure 1. Al Bathah bridge deck configurations.](image-url)

| Material       | Concrete A50 | Steel       |
|----------------|--------------|-------------|
| $E_C$          | 27805.57 MPa | $E_S$       |
| $f' C$         | 35 MPa       | $f_S$       |
| $\nu$          | 0.19         | $\nu$       |
| $\gamma_C$     | 24.5 KN/m3   | $\gamma_S$  |

3. Finite Element Building Model of Bridge Deck

Two of the world's leading software packages for finite element analysis (FEA) that can provide advanced analyzes using finite elements used in this study. The first one, CSI Bridge software (which was used to verify the overall behavior of the bridge deck) and the second one, ABAQUS software (Which was used as a detailed model to study the behavior for the area of the bearing pad).
3.1 CSI Bridge model

In this study, a three-dimensional finite element model of composite simply supported bridge deck was created to investigate their seismic behavior and the element types which were used to simulate the bridge deck in CSI Bridge are shown in Table 2 below:

| Shape components          | Element type          | Geometrical order | Degree of freedom |
|---------------------------|-----------------------|-------------------|-------------------|
| Built up steel girders    | Homogenous shell       | Linear            | 4-node            |
| Reinforced concrete slab  | Layered shell element | Linear            | 4-node            |
| Cross frame diaphragms    | Frame element         | Linear            | 2-node            |
| Elastomeric bearing pads  | Hysteretic isolator link | Linear       | 2-node            |
| Pedestal concrete pads    | Solid element         | Linear            | 8-node            |
| Epoxy layers              | Spring element        | Linear            | 2-node            |
| Shear stud connectors     | Complete bond (constrain) |              |                   |

Reinforced rebar in the concrete deck slab modeled as a smeared layers which defined as an equivalent area of each steel reinforcement divided by the spacing of each rebar as shown in Figure below 2;

![Figure 2. Multi-layer shell element used to model the reinforcement concrete deck slab.](image)

The hysteretic rubber isolator link element used to model the elastomeric bearing pads composite of six spring (shear, pure bending axial, and torsion), which provided linear properties in the vertical direction and nonlinear properties in two other dimensions. Fixed boundary condition assigned to the bottom face of the pedestal concrete pads. The stiffness of spring in three direction calculated from the equation below;

\[
K_{\text{eff}} = K_d + \frac{Q_d}{\Delta} \tag{1}
\]

\[
K_V = \frac{E \cdot A_r}{T_r} \tag{2}
\]

where: \(K_d\) post-elastic stiffness, \(Q_d\) characteristic strength, \(\Delta\) specific displacement, \(A_r\) reduce area of bearing, \(E\) compressive modulus is a function of material constant \(E_c = [1+2KS2]\), \(T_r\) total thickness of elastomer, \(E\) elastic modulus, \(K\) material constant, \(S\) shape factor.
Figure 3. Modeling of the deck using CSI Bridge.

3.2 ABAQUS model

The details about element types used in the ABAQUS model are shown in Table 3.

Table 3: Characteristics of Selected Elements in ABAQUS software.

| Shape components                      | Element type                      | Geometrical order | Degree of freedom |
|---------------------------------------|-----------------------------------|-------------------|-------------------|
| Built up steel girders                | C3D8R (brick element)            | Linear            | 8-node            |
| concrete slab                         |                                   |                   |                   |
| Reinforcement rebar                   | T3D2 (truss element)              | Linear            | 2-node            |
| Cross frame diaphragms                | B31 (beam element)                | Linear            | 2-node            |
| Elastomer                             | C3D8RH (hybrid brick element)     | Linear            | 8-node            |
| Steel sheet plate                     | C3D8R                             | Linear            | 8-node            |
| Pedestal concrete pads                | C3D8R (brick element)             | Linear            | 8-node            |
| Epoxy layers                          | COH3D8 (cohesive element)         | Linear            | 8-node            |
| Shear stud connectors                 | Complete bond (tie constrain)     |                   |                   |

Figure 4. Modeling of the deck using ABAQUS.
4. Input Earthquake Ground Motion
An intense seismic activity with different strengths has been reported for the years 2017 and 2018. More than 70 earthquakes struck Iraq in the last two months of 2017. The magnitude of these earthquakes ranged from 4.0 to 7.3 with depths ranging from 6.21 to 42.32 km, according to the Richter scale. As shown in Figure 4 a major earthquake occurred on 12 November 2017 near the Iran-Iraq border with a magnitude of 7.3 on the Richter scale recorded by the international station. Iraqi observers reported the seismic activity of November 12, 2017, and the first half of the 2018 earthquake. The raw data from these observatories were therefore analyzed and the record of the acceleration time drawn.

![Figure 4](image)

**Figure 5.**Magnitude and depth of earthquakes for the last two months, 2017 and till June, 2018 [Al-Taie and Albusoda, in (2019)]

Loading input data was an acceleration function-time history with a magnitude 4.9 Mw as recorded at the station of Baghdad was used in this study as the input seismic activity Figure 5.

![Figure 6](image)

**Figure 6.** The acceleration time history of November 12, 2017 earthquakes in Baghdad.

5. Analysis Results
The bridge deck under investigation was analyzed under the effect of the self-weight and the earthquake ground motion which was applied in direction perpendicular to the main bridge axis (transverse direction of the bridge deck). This type of bridge decks weak in the transverse direction and their stiffness is not sufficient to generate lateral resistance and makes it the main point in this study. The substructure of the bridge is beyond the scope of this study. The figures below show the analysis results of the bridge deck in two software.

5.1 **CSI Bridge Results**
Figure 7. Three-dimensional view of FEA result of bridge’s superstructure in terms of displacement in transverse direction (unit, mm).

Figure 8. Transverse displacement along the length of girders- top flange of steel girders (unit, mm).

Figure 9. Transverse displacement along the length of girders- bottom flange of girders (unit, mm).

Figure 10. Average longitudinal rotation along the length of girders-web of girders (unit, rad, sec).

Figure 11. Maximum displacement of elastomeric bearing pads on one side of bridge’s superstructure (unit, mm).
5.1.1 Discussion of CSI Bridge Results

The integrated model using CSI Bridge software managed to track the deck’s behavior under earthquake. The stresses in built-up steel girders, the reinforced concrete slab and steel frame diaphragms are all within the materials elastic limits. The concern at the bearings was very clear the displacements at the level of the bearings reached the limits and the entire deck shifted one side as one body and slid from its seat. The limitation of using the link element is that the response of these bearings will only be obtained in forms of displacement limits without providing information on the stresses exerted and this kind of model does not give an indication of the behavior of the bearings in analytical studies during the earthquake, but is only useful for design considerations. To study their response, we need to model the dimensions of the sections of the elastomeric bearing pad and its epoxy attachment layers with steel girders and concrete pedestal pads near the actual state. Therefore, it’s important to use ABAQUS software for these reasons.
5.2 ABAQUS Results

Figure 17. Three-dimensional view of FEA result of the bridge’s superstructure in terms of displacements in the transverse direction (unit, mm).

Figure 18. Three-dimensional view of FEA result of steel girder of the bridge’s superstructure in terms of displacements in the transverse direction (unit, mm).

Figure 19. X-Y view of FEA result of diaphragms in terms of displacements in the transverse direction (unit, mm).
Figure 20. Three-dimensional view of FEA result of elastomeric bearing pads of the bridge’s superstructure in terms of displacements in the transverse direction (unit, mm).

Figure 21. Time-displacement relationships of the nodes at the elastomeric bearing pads of bridge’s superstructure in the transverse direction (unit, mm).

Figure 22. Von Mises stress distribution of steel girders of bridge’s superstructure (unit, N mm).

Figure 23. Stress distribution of diaphragms of bridge’s superstructure (unit, N mm).
Figure 24. Directional stress pattern of elastomeric pads of bridge’s superstructure (unit, N mm).

Table 4. Comparison Between Analysis Results of Bridge Deck Components Obtained From Both Softwares (a) Displacements, (b) Stresses (C) Longitudinal Rotation in the Web of the Girders.

| Components       | CSI Bridge Software | ABAQUS Software |
|------------------|---------------------|-----------------|
|                  | Maximum Displacements (mm) |                  |
| Girder           |                      |                 |
| Top flange       | 280.99               | 229.15          |
| Web              | Do not give the maximum displacement at the web | 200.81          |
| Bottom flange    | 285.35               | 211.64          |
| Diaphragm        | 286.80               | 223.11          |
| Bearing          | 167.7 (Horizontal)   | 158.11 (Horizontal) |
| Concrete pedestal| 5.791E-5             | 0.85            |

(b) Maximum Stresses (MPa)

| Components | Stress Type   | Analysis Software Type |
|------------|---------------|------------------------|
| Deck slab  | Longitudinal stress | 7.65 | 2.08 |
|            | Lateral stress  | Not available | 19.49 |
| Girders    | Longitudinal stress | 128.95 | 84.34 |
| Component                | Type            | Stress | Value (MPa) |
|--------------------------|-----------------|--------|-------------|
| Von Mises lateral stress | Top flange      | Not available | 87.80 |
|                          | bending stress  | Not available |          |
|                          | Bottom flange   | Not available | 169.72 |
|                          | bending stress  | Not available |          |
| Diaphragm                | Axial stress    | Not available | 117 |
|                          | Longitudinal    | Not available | 108.10 |
|                          | stress          | Not available |          |
| Bearing                  | Lateral stress  | Not available | 126.33 |
|                          | Shear stress    | Not available | 75.21 |
| Concrete pedestal        | Lateral stress  | Not available | 2.28 |

6. Conclusions and Recommendations

The three-dimensional finite element model developed in this research using CSI Bridge and ABAQUS software succeeded in tracking the behavior of traditional composite simply supported bridge decks in Iraq when exposed to actual earthquake loading. The most significant finding is that these traditional decks, commonly used in Iraqi bridges and overpasses, will not be able to resist the lateral loading of earthquakes with intensity levels that have already occurred. The main issue is very obvious at the level of the bearings where the entire deck was completely slipped and the deck moved from its place. This situation occurs when there are no live loads on the deck that is still a possible case. The bridge deck displaced as a unit rigid body from its location and the diaphragm effect was irrelevant in increasing the lateral force exerted by earthquakes. Slippage approached 286 mm and 5 steel frame diaphragms stiffened the deck. The bearing displacements were large according to their design specification so these bearings shifted out of position because the epoxy surfaces on the top and bottom sides of the bearing pads weaken and lose their stability due to earthquake loading (horizontal). The stresses in the deck components were all within the materials elastic limits, this is possible since all the built-up energy influencing the deck was liberated from the original position by the motion. In order to resolve these weaknesses in the design of superstructures, it is highly recommended that bridge engineers in Iraq incorporate provisions for earthquakes in their construction design.

7. References

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