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Seismic Performance Assessment of Deteriorating Reinforced Concrete Box Culvert

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ABSTRACT. *A culvert is a crucial component of highways whose proper operation is connected indirectly to the state's economy and the effectiveness and safety of road transportation. Therefore, it is crucial to assess the culvert structure's safety. In this work, a seismic assessment of undamaged and damaged reinforced concrete box culverts is performed. The deterioration in culvert slab thickness over time due to corrosion is considered. The structure was subjected to seismic loading along with standard static loading to observe the performance of a box culvert. The results show that the seismic response of culverts would be influenced by aging and deterioration of slab thickness from its original conditions. The finding of this study highlights the importance of considering the effect of corrosion on the slab thickness when assessing the seismic performance of culverts, as it can have a significant impact on the structure's safety.*

Keywords: Box culvert, damaged, undamaged, seismic assessment.

1. INTRODUCTION

In transportation engineering, a culvert is a common reinforced concrete structure that allows water to flow inside it beneath a road, railroad, or embankment to facilitate and provide a passage for people and vehicles. Box culvert is an essential component of urban infrastructure, and their collapse can result in substantial economic losses and traffic problems [1]. In past earthquakes, in design, it was believed that seismic risk for under-ground structures is much less than that of structures above ground. Low-energy seismic waves cause very little damage to culverts; the reason is that reinforced box culverts (RBCs) are supposed to act in unison with the adjacent soil, and as a result, the lining is not exposed to large seismic forces. RBCs have not been significantly damaged by past major earthquakes that seriously damaged geotechnical structures. However, Kheradi et al. "reported the significant damages caused by several earthquakes: the 1995 Hyogoken-Nambu earthquake that led to the collapse of Daiki Station in the Kobe subway system; the 1999 Turkey earthquake that failed the Bola Highway Tunnel; and the 1999 Chi-Chi earthquake in Taiwan, which caused damage to gas and water pipelines" [2].

Culverts are normally constructed to handle static loads without taking earthquakes into account. However, it is prudent to design big culvert projects placed in seismically active regions to survive structural damage due to seismic activities. Unfortunately, due to a lack of data on substantial damage caused by previous earthquakes, there is no standard seismic design technique. Various seismic design techniques have been used for rectangular underground structures such as cut-and-cover tunnels, which are similar to reinforced concrete box culverts. Researchers have developed several approaches to assess the seismic behavior and design of such structures [3]. These studies are believed to be relevant to the seismic design of RBCs because of the similarities between the cross-section and member materials of RBCs and underground structures mentioned earlier. However, structural features such as the wide cross-section and sidewalls without haunches at the bottom make it distinctive. Although dynamic analyses have been validated and there have been earlier experimental investigations [4] in this field, these studies examined RBCs under various seismic loading conditions, but fast, economic, and FEM-based study is still needed for seismic assessment of aged/existing culverts and seismic design of new ones. Therefore, the aim of this research is the seismic assessment of two models (undamaged and damaged with aging) of RBCs is conducted with earthquake loading along with static loading to assess the seismic behavior of RBCs and evaluate their seismic performance with aging.

2. METHOD AND MATERIALS

2.1 Materials

The reinforced concrete box culvert model consists of M30 concrete and G60 steel rebars. The properties of undamaged and damaged concrete and steel materials are given in Table 1. The modulus of elasticity of materials was assumed to be 10 % of the original value due to extreme corrosion. The concrete damaged plasticity model (CDP), which offers a general capability for modeling concrete material, was used in finite element modeling to define the inelastic behavior of concrete [4]. The data used for concrete-damaged plasticity for modeling is illustrated in Table 2.

Table -1: Parameters of parts used in the model

Parts	Density(ρ)	Elastic Modulus(E)	Poisson ratio(v)
Undamaged concrete	2400 kg/m^3	34 GPa	0.21
Damaged concrete		3.4 GPa	
Undamaged steel	7850 kg/m^3	200 GPa	0.3
Damaged steel		20 GPa	

Table -2: Concrete Plastic damaged model parameters

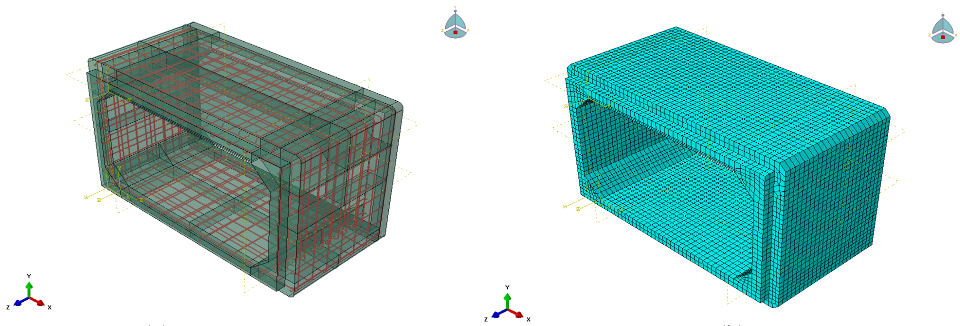
Parts	Dilation Angle	Eccentricity	s_{b0}/s_{c0}	K	Viscosity Parameter
Concrete	40	0.1	1.16	0	0

2.2 Geometry and Model details

The geometry of the model is selected with reinforcement according to ASTM C1577 for the culvert. Figure 1(a) shows the geometry modeled in ABAQUS software. The dimension of the culvert structure is 2120 x 1220 x 203 mm, and the reinforcement cage is made with 10 mm diameter bars with a spacing of 180 mm. The embedded element technique is used to create a bond between concrete and steel. The interaction module constrained the steel cages within the concrete, effectively making concrete the host material. Hence, the rebar elements are limited to having the same translations and rotations as that of the host element concrete [5]. The model was discretized with a mesh size of 50 mm. Decreasing the mesh size increased the accuracy but required high computation time and vice versa. For the modeling of corrosion damage in the culvert, a 50-year-old culvert was considered whose slab thickness would be reduced by 145 mm due to aging [6]. Table 3 summarizes the mean corrosion thickness of the top slab with age in undamaged and damaged models.

Table -3: Mean corrosion thickness of the top slab with age

Time (Years.)	Mean Corrosion Thickness (mm)	Remaining Thickness of the slab(mm)
0	0	226.3
50	145	81.3



(a) (b)

Fig -1: Details of FEM of box culvert (a) Reinforcement cage embedded in concrete (b) Mesh of Finite Element Model (FEM)

2.3 Loading and Boundary conditions

The model is loaded with active earth pressure on side walls, a surcharge of soil and pavement load on the slab of the culvert, water pressure inside the culvert, pore water pressure on the outside of the culvert, and traffic load over the culvert slab. The values of these loads are obtained from the literature [6] and the application of these loads are depicted in figure 2. The boundary conditions are applied to the culvert to simulate the in-situ conditions as shown in figure 2.

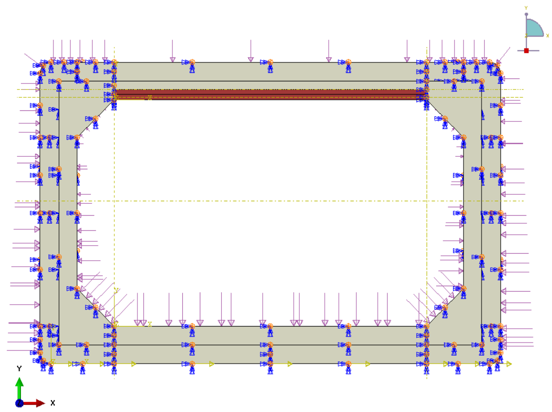


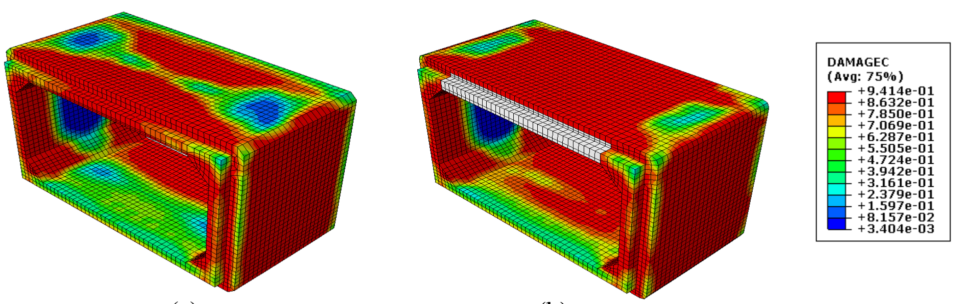
Fig -2: Loading and boundary conditions of a box culvert

2.4 Earthquake Excitation

The well-known Kobe earthquake with a magnitude of 7.2 on the Richter scale has opted for seismic analysis of culverts that have caused destruction to many structures. The earthquake wave is applied for 7 seconds at the base of models in the x-direction and the response of undamaged and damaged models are observed. The results of the analysis are provided in the following section.

3. RESULTS AND DISCUSSION

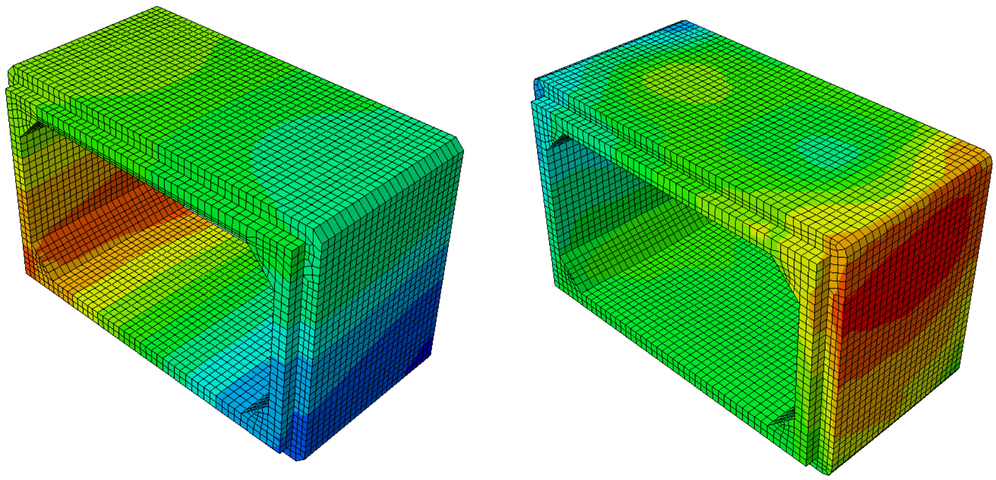
The results of the damage analysis, as shown in Figure 3, indicated that the model with a deteriorated portion of the slab was damaged more as compared to the undeteriorated model. Furthermore, the deformation of the box culverts is compared in figure 4. The culvert with extreme corrosion of 145mm endured the larger deformation on the right wall.



(a) (b)

Fig -3: Compression damage of box culvert (a) Undamaged model (b) Damaged model

Figure 5 showed the maximum deformation response of both models in the x-direction (U1), where it was observed that the maximum deformation occurred for the deteriorated culvert where the peak deformation was at a time instant of 2.9 seconds of the earthquake excitation. Overall, the deterioration of the slab thickness can significantly impact the structure's safety, and the seismic response of culverts would be influenced by the aging and deterioration of the slab thickness from its original conditions.



(a) (b)

Fig -4: Deformation of models (a) Undamaged model (b) Damaged model

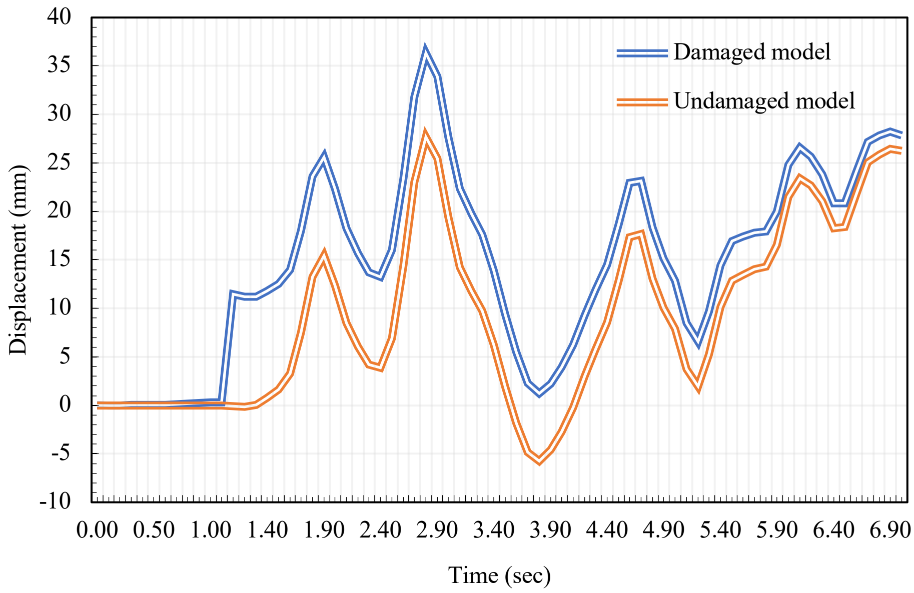


Fig -5: Displacement versus time response of undeteriorated and deteriorated models

4. CONCLUSION AND RECOMMENDATIONS

In this study, the seismic performance of undamaged and damaged reinforced concrete box culverts were assessed by simulating the Kobe earthquake of magnitude 7.2. The deterioration in the culvert slab's thickness due to corrosion was considered and the structure was exposed to seismic loading along with standard static loading. The study concludes that the seismic response of reinforced concrete box culverts is affected by the aging and deterioration of slab thickness due to corrosion.

- The model with a deteriorated portion of the slab was damaged more as compared to the undeteriorated model.
- A larger deformation was observed in the box culvert with extreme corrosion. The discrepancy in the response of the structure could be expected if the aging effect of the structure will be ignored.
- The study recommends the importance of considering the effect of corrosion on slab thickness when

assessing the seismic performance of culverts for an accurate assessment of the safety of the structure.

In the future, existing culverts in seismically active areas could be evaluated through Finite Element Method (FEM) analysis to assess their structural integrity and determine if they need to be treated or replaced. Moreover, this study assumed a reduced modulus of elasticity of materials (10% of actual) for the damaged portion of the slab. Further research is also needed to determine the effects of corrosion more accurately on the materials.

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