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Nonlinear seismic response of a masonry arch bridge

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Abstract. Historical structures that function as a bridge from past to present are the cultural and social reflections of societies. Masonry bridges are one of the important historical structures. These bridges are vulnerable against to seismic action. In this study, linear and non-linear dynamic analyses of historical Nadir Bridge are assessed. The bridge is modelled with three dimensional finite elements. For the seismic effect, artificial acceleration records are generated considering the seismic characteristics of the region where the bridge is located. Seismic response of the bridge is investigated.

Keywords: masonry bridges; finite element model; linear and non-linear dynamic analysis; seismic response

1. Introduction

Masonry material is one of the oldest construction system have been used for hundreds of years (Bayraktar *et al*. 2008, Muvafık 2014, Preciado *et al*. 2015). Historical structures that function as a bridge from past to present are the cultural and social reflections of societies. These structures, which date back to thousands of years, have frequently been damaged or ruined against dynamic loadings such as traffic, wind and especially earthquakes. Turkey has a large number of historical structures. Masonry bridges are one of the important historical structures for cultural heritage of a country, and protection of these structures is important for the next generation. These structures have low ductility and due to their stiff and brittle structural components, they are usually severely damaged during strong earthquakes (İlerisoy and Soyluk 2012). Masonry arch bridges are one of the oldest forms of bridge construction. These bridges were built from the beginning of the earliest civilization and constructed various sizes, styles and spans. They certainly provide a particular service for transportation networks, carrying people and vehicles, or aqueducts carrying water. A total of 1266 bridges were built in Turkey from the time of the Hittites until the Ottoman Empire. 112 bridges are in the highways network, 53 are on state highways and 59 on provincial highways, while the remainders serve village roads. Many studies exist about finite element analysis of masonry bridges (Brencich and Sabia 2008, Pela *et al*. 2009, Bayraktar *et al*. 2010, Altunışık *et al*. 2011). Beside these papers, Frunzio *et al*. (2001) conducted three dimensional finite element analysis of a stone masonry arch bridge. In this study, the analysis is involved the structural manner of the spandrel walls and fill material. Fanning and Boothby (2001) assessed three

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masonry arch bridges by using finite element method under service loads. Smeared crack and Drucker-Prager material models were used for masonry material and fill material, respectively. The numerical results were compared with field test results of the bridges. Toker and Unay (2004) studied behaviour of the prototype masonry arch bridge by finite element analysis under different loading conditions. Ural (2005) evaluated earthquake performance of Çoşandere masonry arch bridge using El Centro acceleration records. Wang and Melbourne (2007) generated two finite element models, a simple soil-arch interaction and full bridge model, using a commercial finite element package. In the full bridge model, the smeared crack approach is adopted for modelling the masonry and soil is simulated with a Drucker-Prager material model. Beconcini *et al.* (2007) investigated the dynamic characterization of a five spans historic masonry arch bridge which was strengthened due to the failure of a pier. Sevim *et al.* (2011a) evaluated the nonlinear seismic performance of a restored historical masonry bridge considering the acceleration record of Erzincan earthquake in 1992. Sevim *et al.* (2011b) used ANSYS finite element program for finite element modelling of two historical arch bridges. After the analytical study, ambient vibration tests were conducted to experimentally obtain dynamic characteristics of these bridges and finite element models were updated. Time-history analyses of the two bridges were performed for updated finite element models using 1992 Erzincan earthquake records. Radnić *et al.* (2012) assessed static and dynamic analysis of the old stone bridge in Mostar. In the paper, they analysed the influence of vertical load, temperature change and real earthquake action. Gonen *et al.* (2013) assessed deformations and stresses of the historical masonry arch bridge under dead loads. Linear elastic response of the bridge was investigated.

The objective of this study is nonlinear earthquake performance of the historical Nadir bridge which located Darende in Malatya. The Nadir Bridge, which built in 1569, is an Ottoman structure. It is 50 m long and 3.90 m wide. It has three arches. The restoration of this bridge is completed by Turkish General Directorate of Highways in 2008. For numerical modelling, arch, spandrel walls and fill material of the bridge are modelled with three dimensional finite elements. For arch and spandrel walls, smeared crack model which includes the strain softening is used. For fill material, Drucker-Prager material model which include elasto-plastic behaviour is used. For the seismic effect, artificial acceleration records are generated considering the seismic characteristics of the region where the bridge is located. The predictor-corrector technique is used in conjunction with the HHT-α method to solve the non-linear dynamic equation. Linear and non-linear analyses are performed and effects of cracking on the seismic response of Nadir Bridge are discussed.

2. Nadir bridge

The case study structure is the Nadir Bridge located in Darende which is small town of Malatya, Turkey. The bridge is placed over the Tohma River. It was built in 1569 during the Ottoman period. Some views of the Nadir Bridge are shown in Fig. 1.

The restoration of this bridge was completed by Turkish General Directorate of Highways in 2008. The bridge is 50.14 m long and 3.90 m wide. Spandrel wall thickness is 0.65 m. It has three arches. The biggest arch span is 7.90 m. The bridge has 0.30×0.60 m^2 dimensional parapets on both sides of the bridge deck. It has also a thin stone pavement surface on the filling material.

This bridge was not used as an important transportation link today. Geometrical properties of the bridge are presented in Fig. 2.

Fig. 1 Views of the Nadir Bridge

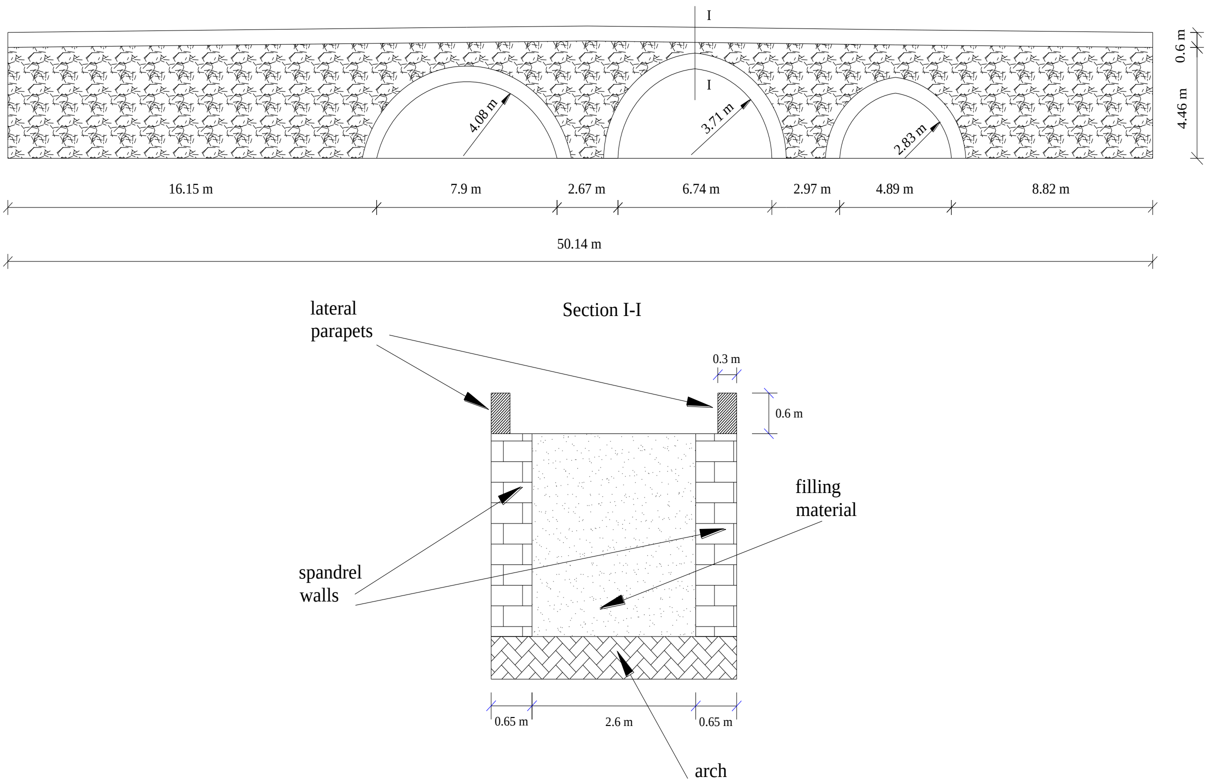
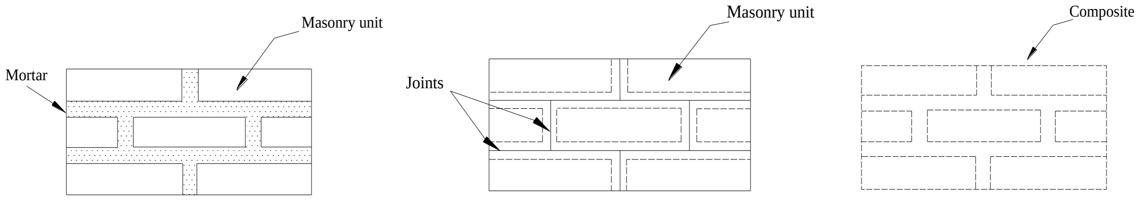


Fig. 2 Geometrical properties of the Nadir Bridge

Masonry is a heterogeneous material which exhibits distinct directional properties due to the mortar joints which act as planes of weakness. The numerical analysis of masonry structures is mostly carried out by using finite element method. In general, the approach towards the numerical representation of masonry can focus on the micro-modelling of the individual components, unit (brick, block, etc.) and mortar, or the macro-modelling of masonry as a composite (Rots 1991, Lourenço 1996). Depending on the level of accuracy and the simplicity desired, three modelling



(a) Detailed micro-modeling (b) Simplified micro-modeling (c) Macro-modeling

Fig. 3 Modelling approaches for masonry structures

approaches commonly used for modelling masonry structures. These modelling approaches are given in Fig. 3.

In detailed micro-modelling approach, Young's modulus, Poisson's ratio and, optionally, inelastic properties of both unit and mortar are taken into account separately. This approach is one of the best modelling strategies for modelling the masonry structures. However, it needs higher computational effort. For this reason this type of modelling applies notably to structural details. In simplified micro-modelling approach, each joint, consisting of mortar and the two unit-mortar interfaces, is lumped into an average interface while the units are expanded in order to keep the geometry unchanged. Masonry is thus considered as a set of elastic blocks bonded by potential fracture/slip lines at the joints. In macro-modelling approach, the masonry accepts as a composite without making a distinction between unit and mortar. This modelling technique is commonly preferred because it decreased the computer solution time significantly in the modelling of big structural systems. Different modelling approaches that mentioned above can be used depending on the size of the structure and purpose of the analysis. For this reason, it is not suitable to make comparison of different modelling approaches. Because of its low computational effort, macro-modelling approach is commonly used in the literature (Bernardeschi *et al.* 2004, Carpinteri *et al.* 2005, Pela *et al.* 2013, Zampieri *et al.* 2015).

3. Numerical application

In this study, nonlinear seismic response of the historical Nadir Bridge which located Darende in Malatya was presented. Three dimensional model of the bridge was generated using ANSYS (2008) finite element software. In the finite element modeling, SOLID65 element which is capable of cracking in tension and crushing in compression is used from ANSYS (2008) library for masonry materials. The element has eight nodes and has three translation degrees of freedom on *x*, *y*, *z* directions. Also, the SOLID65 element is used many numerical studies to determine both linear and nonlinear behavior of masonry structures (Fanning and Boothby 2001, Lü *et al*. 2011, Li and Atamturktur 2014). The SOLID65 element provides nonlinear response for brittle materials depends upon a constitutive model for the triaxial behaviour of concrete (William and Warnke 1975). The element uses a smeared crack analogy for cracking in tension zones and considers plasticity algorithm for crushing in compression zones. It allows the formation of cracks perpendicular to the direction of principal stress that exceeds the tensile strength of the masonry material. Cracking and crushing occur at integration points of the element. Linear elastic manner is observed until the tensile or compressive strengths of the material are exceed. If the element

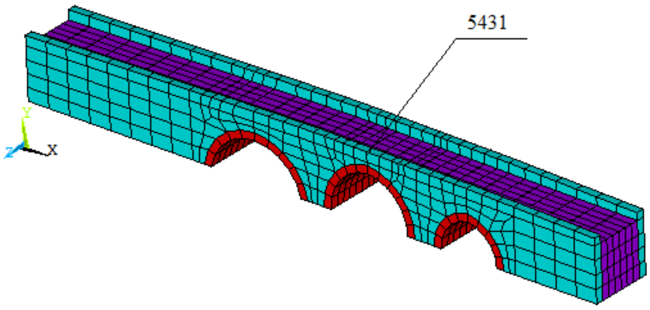


Fig. 4 Three dimensional finite element of the bridge

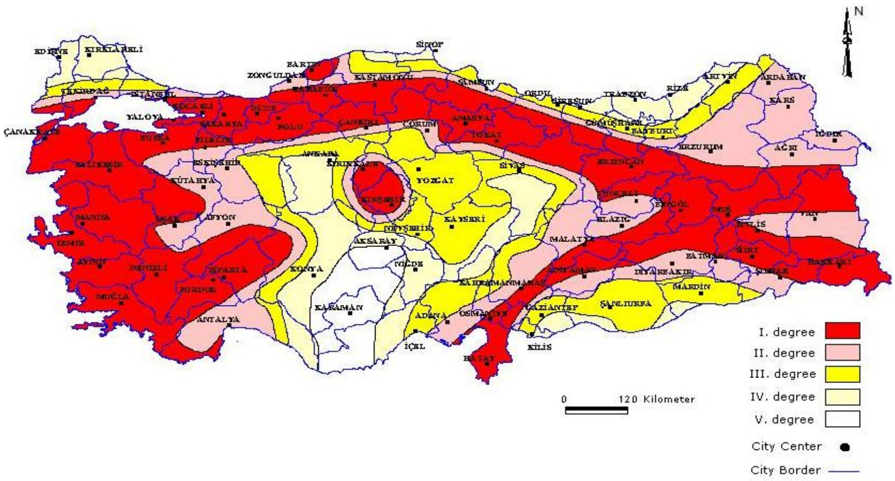


Fig. 5 Seismic zone map of Turkey

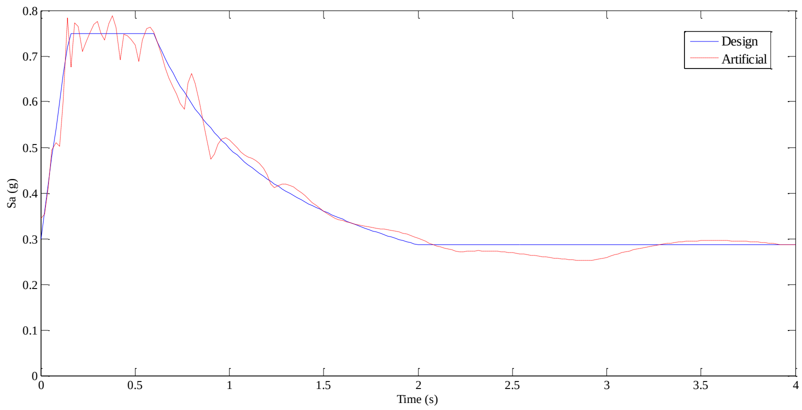
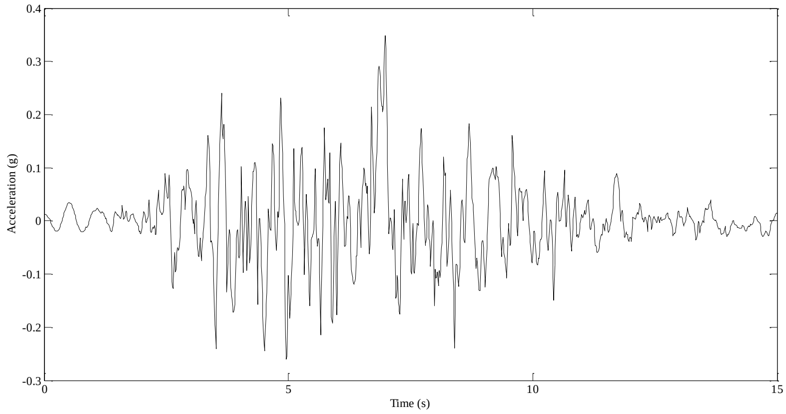
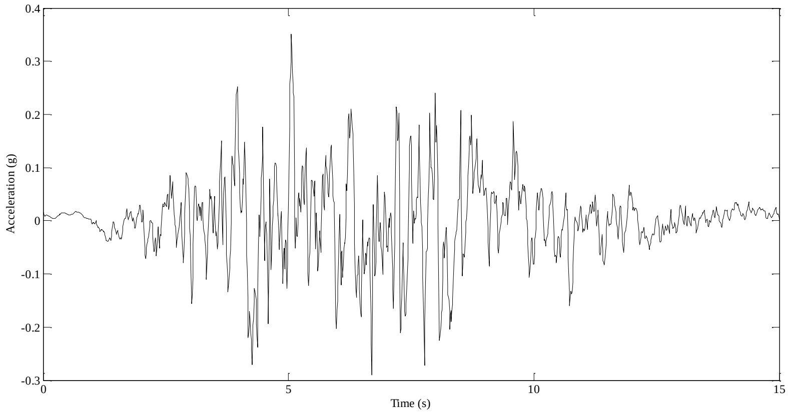


Fig. 6 Artificial and design acceleration spectrum

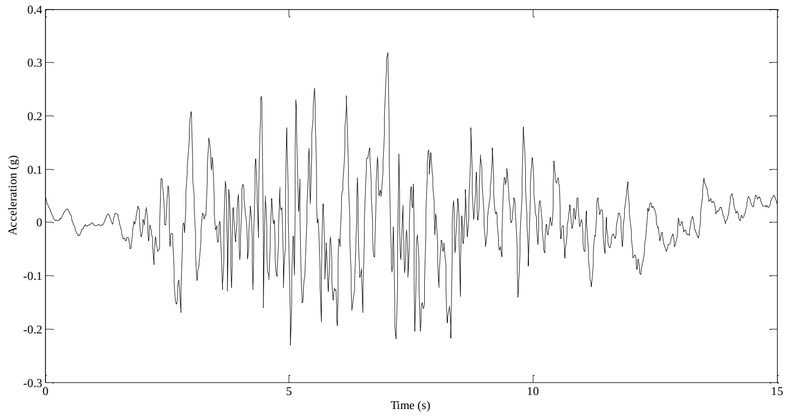
principal stress exceeds the tensile or compressive strength of the material, cracking or crushing occur perpendicular to the relevant principal stress direction at integration point of the element. Stress-strain relation of this point is modified. For the fill material, Drucker-Prager material model



(a) *x* component



(b) *y* component



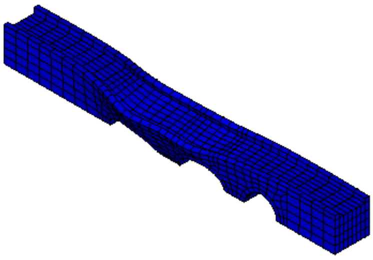
(c) *z* component

Fig. 7 Artificial earthquake acceleration records

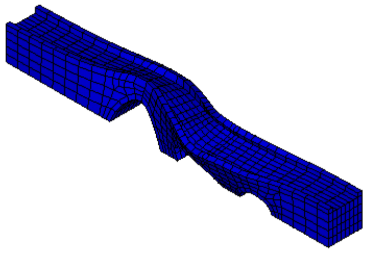
was used. The Drucker-Prager criterion is a simple modification of the Von Mises criterion which includes the effect of hydrostatic stress. The Drucker-Prager surface which express depending on

Table 1 Properties of the material used in the analysis

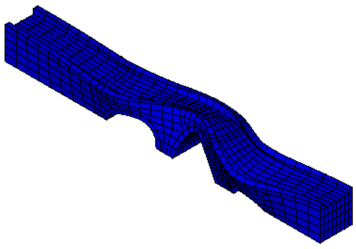
Arch				Spandrel wall				Filling material				
Young modulus (Mpa)	Density (t/m^3)	Poisson ratio	Tensile strength (Mpa)	Young modulus (Mpa)	Density (t/m^3)	Poisson ratio	Tensile strength (Mpa)	Young modulus (Mpa)	Density (t/m^3)	Poisson ratio	Cohesion (Mpa)	Friction angle (^{o})
2500	2.3	0.2	0.5	2000	2.2	0.2	0.4	1200	1.4	0.25	0.35	40



(a) first mode (f_1=14.626 Hz)



(b) second mode (f_2=16.849 Hz)



(c) third mode (f_3=20.221 Hz)

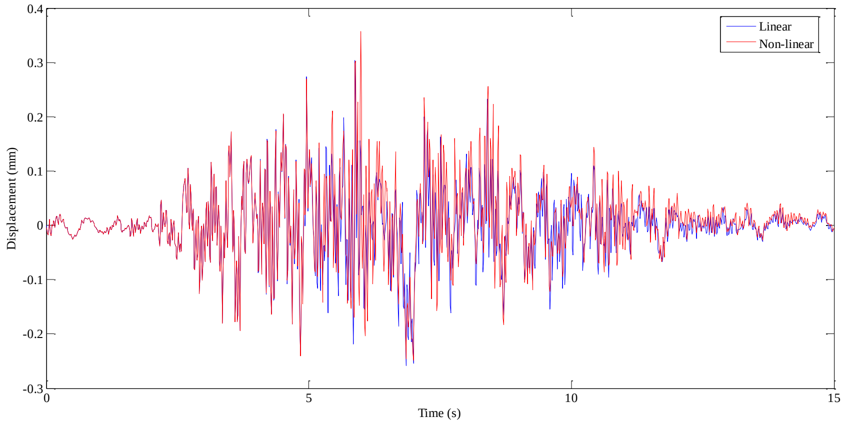
Fig. 8 Mode shapes of Nadir bridge

the cohesion, c, and the friction angle, ϕ is like a right-circular cone. Three dimensional finite element model of the bridge is given in Fig. 4. One nodal point (5431) is marked on the finite element mesh of the bridge to plot the time history of the displacement. 5548 nodal points and 1320 eight noded SOLID65 elements are used in the finite element model of the bridge.

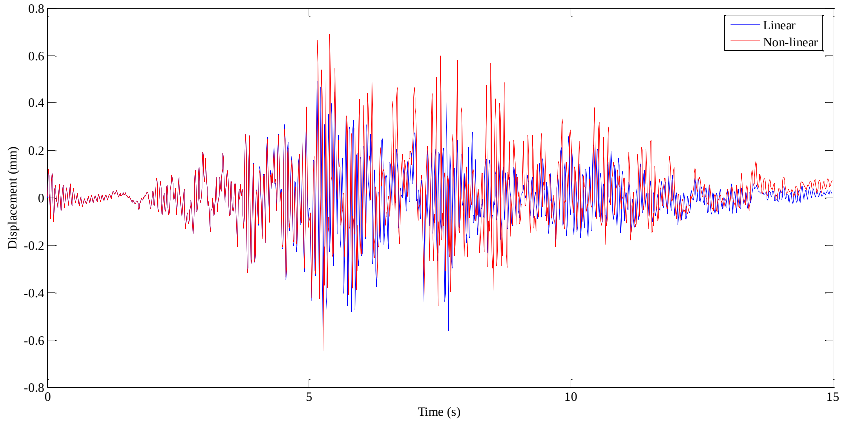
According to seismic zone map, which was prepared by Ministry of Public Works and Settlement, Turkey is divided into the five seismic zones (Fig. 5). Malatya is situated in the first and second earthquake zones. Darende township which is located 106 km north-west of Malatya is at second-degree in accordance with this map. First-degree zone is the most hazardous and fifth-degree zone is no hazard zone with respect to Turkish Earthquake Code (TEC-2007). The maximum acceleration is 0.3 g in the second-degree zone in this code (g is the gravitational acceleration).

By taking this acceleration value into consideration, three artificial earthquake acceleration records compatible with TEC-2007 design spectrum were produced by using SeismoArtif (2013) program. The artificial and design acceleration spectrum curve was given in Fig. 6. For seismic input, these artificial earthquake acceleration records are used in the x, y and z direction of the bridge (Fig. 7).

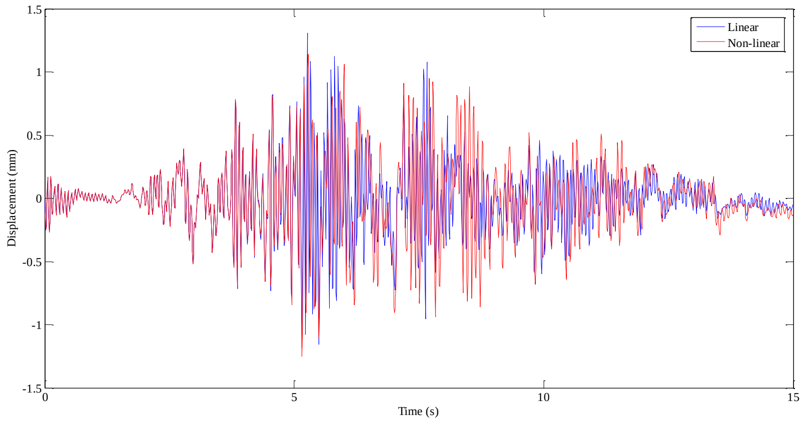
It is difficult to decide the material properties of the historical structures. Therefore, similar



(a) *x* component



(b) *y* component



(c) *z* component

Fig. 9 Time histories of the displacement at nodal point 5431

material properties in the relevant literature are considered in this study (Table 1). Compressive strength of the arch and spandrel wall was considered as 10Mpa and 8Mpa, respectively.

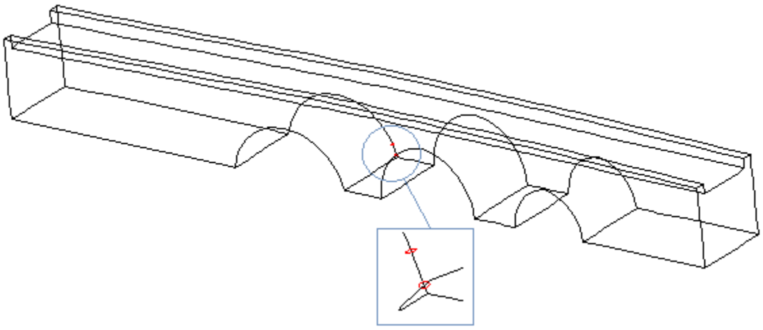
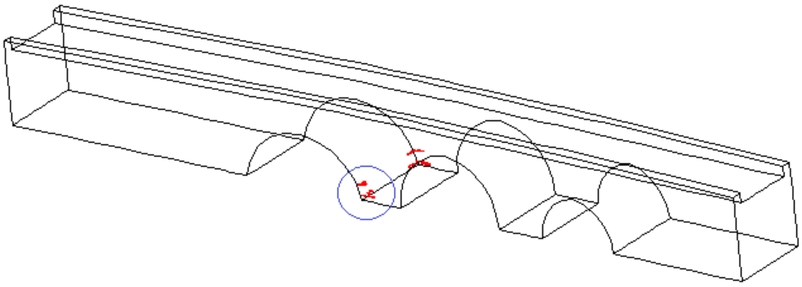
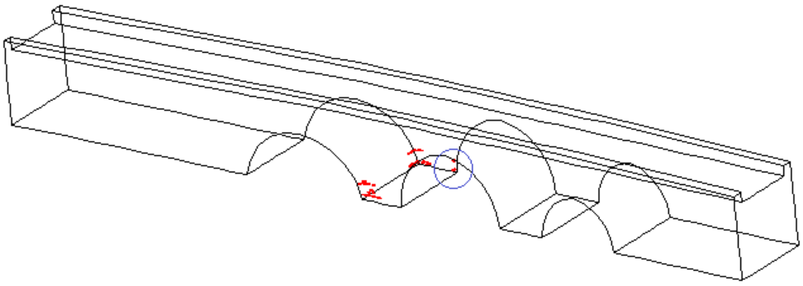


Fig. 10 First crack at the Nadir bridge at t=3.82 s



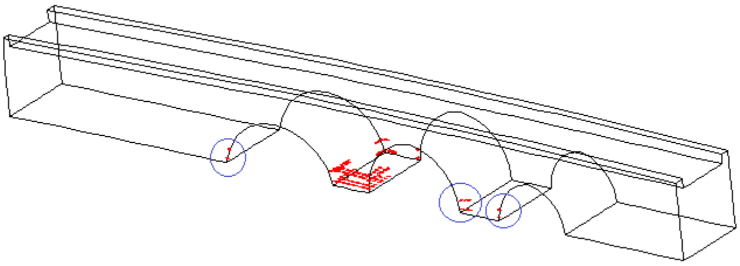
(a) t=4.95 s



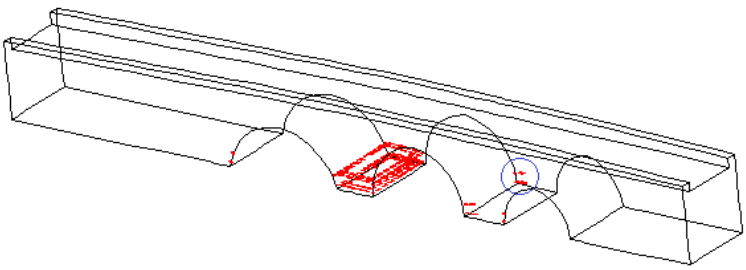
(b) t=5.13 s

Fig. 11 Crack zones at the Nadir bridge at t=4.95 s and t=5.13 s

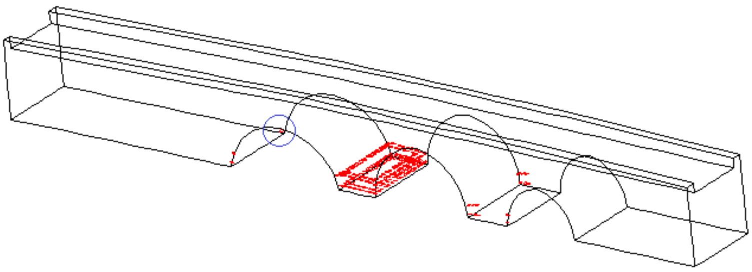
To solve the non-linear dynamic equation, the predictor-corrector technique was used in conjunction with the HHT-α method (Chung and Hulbert 1993). Integration time step was selected as 0.001 s. Stiffness proportional viscous damping ratio was selected as 5% both linear and nonlinear analysis. The solutions were obtained by using ANSYS (2008) finite element program. All degrees of freedom at the base of the model were assumed as fixed. The first three mode shapes and natural frequencies of the bridge are given in Fig. 8. Linear and non-linear solutions of the x, y and z directions of the displacement values of the nodal point 5431 are presented in Fig. 9. Linear and non-linear solutions of the graphs are the same in terms of amplitude up to the consisted first crack (t=3.82 s). Significant difference is occurred at displacement amplitudes due to the cracking and damages after this time. Time histories of the displacement obtained from the both solutions (linear and non-linear) separate with each other as the cracks propagate in the bridge. The first crack is observed at the bottom of the right spandrel wall of the left arch at the upstream face of the bridge at t=3.82 s (Fig. 10). In this region, the cracks are expanded in the x and z directions of the arch. New crack zones are occurred at the bottom of the right spandrel wall of the left arch at the downstream face of the bridge at t=4.95 s. and at the bottom of the left spandrel wall of the middle arch at the upstream face of the bridge at t=5.13 s. (Fig. 11). Existing crack zones are expanded at the region between the left and middle arch. Addition to these crack zones, new crack zones are occurred at the bottom of the left spandrel wall of the left and right arches and right spandrel wall of the middle arch at the upstream face of the bridge at t=5.16 s. (Fig. 12(a)). Furthermore, the additional crack zones are occurred at the bottom of the right spandrel wall of the middle arch at t=6 s. and at the bottom of the left spandrel wall of the left arch at t=7.69 s. at the upstream face of the bridge (Figs. 12(b), (c)). In these crack zones, the tensile stresses exceed the tensile strength of the material and no significant increase in the crack propagation was observed in the subsequent time steps. The bridge did not collapse during the non-linear analyses. The damage level which occurred at the end of the analysis did not affect the safety of the bridge.



(a) t=5.16 s



(b) t=6 s



(c) t=7.69 s

Fig. 12 Crack zones at the Nadir bridge t=5.16 s, 6 s and 7.69 s

4. Conclusions

In this study, nonlinear seismic response of the Nadir Bridge located in Malatya was investigated. Three dimensional finite element model of the bridge was modelled in ANSYS (2008) software using macro modelling approach. For the seismic effect, artificial acceleration records which considering the seismic characteristics of the region were used. Predictor-corrector form of HHT-α integration technique was used for the dynamic solutions. The first crack was observed (t=3.82 s) at the bottom of the right spandrel wall of the left arch at the upstream face of the bridge. At this region, stress values increased and the tensile stresses exceed the tensile strength of the material. Furthermore, the additional crack zones were observed at spandrel walls of the bridge in later time steps. It was seen that linear and non-linear dynamic solutions were the same until the first crack was formed at the bridge. After the first crack, the displacement amplitudes of the linear and non-linear solutions separated from each other. But the bridge did not collapse after the non-linear analysis.

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