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Strengthening the Water Underground Concrete Reservoirs Using the FRP Materials

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Abstract: *The goal of current research was to strengthen water underground concrete reservoirs using FRP materials. So, in this research, first of all, structural system, seismic behavior of concrete underground reservoirs, damage to them and their failure mechanism have been shown. Then, hydrodynamics behavior of reservoirs and issues of water and structure interactions have been reviewed. After all, it has been referred to a strengthening method with FRP composite fibers and their application in seismic strength of structures. Finally, these results have been compared with the modelling of underground concrete reservoir using the ABAQUS software and reservoir's dynamic behavior in normal mode and strength mode have been reviewed (with FRP fibers). Furthermore, suitable approaches have been presented for strengthening this kind of reservoirs. According to obtained results, acceleration maps had the largest damage to reservoir walls, because they had the maximum amount of ground acceleration. So, they must be strengthened with the best solution. Thus, according to the conducted modelling and review of the previous studies and research and considering the strength of performance work, using FRP materials can be one of the main and effective solutions for this ground.*

Keywords: *Underground concrete reservoirs, Strengthening, FRP composite fibers*

INTRODUCTION

Evaluation and safety equipment of underground concrete reservoirs maintaining water are an important subject of country and defense issues. So, designing, construction and maintenance of reservoirs which are used to store water are important considering the population growth and development suburb and urban areas. According to application of the water storage tanks, review of their behavior is very important when an earthquake happens. These structures must be used after earthquake, because they estimate primary needs such as water supply during fire and water supply of people. Thus, correct knowledge of seismic behavior of these kinds of structures is essential for their safety and reduction of maintenance cost. Damages to underground concrete reservoirs show the inadequate resistance of these reservoirs against the side-loads due to earthquake during the past earthquakes. Reviewing the conducted studies on concrete reservoirs showed that Haskins has done the primary studies on reservoirs. He studied theoretical and experimental response of the

system to earthquake's horizontal motion effect considering a tank with rigid walls connected to foundation (Hoskins and Jacobsen, 1934). In reservoir issue, one of the most effective factors on design is hydrodynamic force. The primary main research on obtaining forces induced by earthquake was done by Jacobsen in circular reservoirs containing fluids (Jacobsen, 1949). He calculated hydrodynamic pressure entered into the wall of cylindrical tanks whose foundation were affected by horizontal dynamic simulation. He obtained the velocity of liquid particles through different points (Jacobsen, 1949). Veletsos et al. (1977) studied on dynamic response of circular concrete reservoirs under vertical simulation in rigid flexible walls. They showed that soil and structure interactions cause to reduce the maximum of hydrodynamics pressure induced by earthquake simulation. It was shown that hydrodynamics' pressure induced by hard section of liquid increases considering the flexibility of walls (Veletsos and Auyang, 1977). Fischer (1979), did plenty of studies on the effect of wall flexibility on dynamic response of reservoirs. It showed that flexibility influences so much over hydrodynamics pressures as well as created forces (Fischer, 1979). Studies and reports of damages to tanks in earthquakes showed that the flexibility of walls and the effect of vertical component of earthquake must also be considered in the design of reservoirs. In this regard, Haroon and Husner (1981) presented Husner's main model considering the flexible behavior of the reservoir. One research was done by Kim, Park et al. for dynamic analysis of rectangular reservoirs. They used a combination of finite elements and boundary elements to calculate responses (Koh, Kim and Park, 1998). Also, Ghods and Shenaiee (2014), reviewed and strengthened concrete reservoirs by Fibre-Reinforced Polymer (FRP). Reviews have shown that water concrete reservoirs are reinforced by brief map of management and planning organization of Iran as well as armed steel bars, currently. In fact, fatigue behavior of bars causes to reduce life-cycle and reservoir resistance and wastes huge investments, so strengthening water concrete reservoirs with FRP is essential. Thus, the goal of the current research was strengthening water underground concrete reservoirs using the FRP materials.

Research Method

Considering the goal of the current research which was strengthening water underground concrete reservoirs using the FRP materials, first of all, it has been shown the structural system, seismic behavior of underground concrete reservoirs and damages to them and their failure mechanism. Then, hydrodynamics of tanks, structure and water interactions have been reviewed. After all, it has been referred to strengthening method with FRP composite fibers and its application in seismic strength of structures. At last, it has been compared with the modelling of underground concrete reservoir using the ABAQUS software and the reservoir dynamic behavior in normal mode and strength mode (with FRP fibers) have been reviewed. In this research, specification of the used steel has come in Table 1. According to the mentioned numbers, it can be said that the behavior of the model has used von-Mises criteria.

Table 1. Specification of the steel materials

(kg/m ³) ρ	E (GPa)	ν	f_y (MPa)
7850	200	0/3	420

An important problem of the modelling of the steel in the range of plastic is that engineering stress or strain are obtained from the results of the tensile test of the device. Equations below, have been used to transform engineering stress and strain to the true stress and strain. True stress and strain must be used to identify the plastic behavior of the material to ABAQUS software.

$$\varepsilon = \ln (1+\varepsilon_0) \quad (1)$$

$$\sigma = \sigma_0 (1 + \epsilon_0) \tag{2}$$

Where ϵ_0 and σ_0 are engineering strain and engineering stress, respectively and ϵ and σ are true strain and true stress, respectively. Considering the above point, the obtained stresses and strains from the tensile test convert into true stress and strain. They are considered in Table 2.

Table 2. Plastic strain and stress of steel materials (Mokhatar and Abdullah, 2012)

YIELD stress(MPa)	plastic strain
300	0
310	0.01
350	0.1
400	0.5

In Table 2, the first column shows true stresses and the second column shows true strains, where stress values were in Pascal.

Concrete materials as well as the combination model of Concrete Damaged Plasticity has been used in this model. This behavior model is the most complex and applicable model for concrete materials which has been used in ABAQUS software. This behavior model is able to simulate concrete cycle behavior well. The parameters required to model water are given in Table 4 and mechanical specification of CFRP composite materials required to enter into software are given in Table 5.

Table 3. The definition of the function of compressive and tensile properties of concrete (Mokhatar and Abdullah, 2012)

Yield Stress	Inelastic Strain	Damage Parameter
14280000	0	0
17920000	5.50E-05	0
21000000	0.000132	0
23520000	0.000232	0
25480000	0.000354	0
26880000	0.000498	0
27720000	0.000665	0
28000000	0.000853	0
27720000	0.001065	0.01
26880000	0.001298	0.04
25480000	0.001554	0.09
23520000	0.001832	0.16
21000000	0.002132	0.25
17920000	0.002455	0.36
14280000	0.0028	0.49
10080000	0.003167	0.64

Table 4. The definition of the function of tensile properties of the concrete (Mokhatar and Abdullah, 2012)

Damage Parameter	Cracking Strain	Yield Stress(Pa)
0	0	2800000
0.99	0.0011	28000

Table 5. Plasticity specification of the concrete (Mokhatar and Abdullah, 2012)

Viscosity parameter	Kc	σ_{bo}/σ_{co}	Off-axis	Expansion angle
0	0.666	1.16	0.1	30.5

Table 6. The parameters required to model water in ABAQUS software

Gama	S	Sound speed C ⁰	Dynamic Viscosity	Density
0	0	1450	0/001	980kg/m ³

Table 7. Mechanical specification of CFRP composite materials

E ₂ =55	E ₁ =72	Elastic modulus GPa
u ₁₃ =0.00	u ₁₂ =0.28	Poisson's ratio
G ₁₃ =39	G ₁₂ =35	Shear modulus GPa

Among the existing elements in the current study in ABAQUA, all elements have been used in a form of cube except of crack element.

Modelling calculation

In this section, calculation related to the hard liquid mode and wavy liquid mode, calculation related to the overturning anchor and wave height have been done based on the regulation 123 of management and planning organization of Iran to use in ABAQUS software.

$$W_{wall} = 43200 \text{ Kg the weight of walls} \quad (3)$$

$$W_b = 165814 \text{ Kg the weight of the floor} \quad (4)$$

$$W_{water} = 51638 \text{ Kg the weight of water} \quad (5)$$

Analysis along X

$$\frac{h}{l} = 0.57 \quad (6)$$

$$\frac{w_i}{w} = 0.58 \quad (7)$$

$$\frac{w_c}{w} = 0.38 \quad (8)$$

$$\frac{h_i}{l} = 0.375 \quad (9)$$

$$\frac{h_c}{h} = 0.6 \quad (10)$$

$$\frac{h_i^*}{h} = 0.7 \quad (11)$$

$$\frac{h_c^*}{h} = 0.8 \quad (12)$$

$$w_i + w_c = 49572 \text{ kg} \quad (13)$$

$$\frac{(w_i + w_c)}{w_{water}} = 0.96 \quad (14)$$

The total of hard liquid mode and wavy mode were lower than the total of water weight (4%).

- Time period of source

Time period of rectangular underground reservoirs in hard liquid mode was equal to:

$$T_i = 2\pi * \sqrt{\frac{d}{g}} = 0.49 \quad (15)$$

$$\bar{h} = \frac{\frac{W_i h_i + W_w h_w}{2}}{\frac{W_i + W_w}{2}} = 1.17 \text{ m} \quad (16)$$

$$q = \frac{\frac{W_i + W_w}{2}}{Bh} = 2.2 \text{ t/m}^2 \quad (17)$$

Time period of wavy liquid mode was equal to:

$$C_c = \frac{2\pi}{\sqrt{3.16 \tanh(3.16(\frac{h}{l}))}} = 3.65 \text{ sec} \quad (18)$$

Vertical seismic coefficient was equal to:

$$A = 0.3 \quad (19)$$

$$I = 1.4 \quad (20)$$

$$R = 3 \quad (21)$$

According to regulation, it was 2800.

$$C_i = \frac{A*B*I}{R} = 0.35 \quad (22)$$

$$C_c = \frac{A*B*I}{R} = 0.2 \quad (23)$$

Base cut below source wall in hard liquid mode was:

$$V_i = C_i * (W_i + W_w + W_t) = \frac{25}{6} \text{ Ton} \quad (24)$$

Base cut below source wall in wavy liquid mode was:

$$V_c = C_c (w_c) = 4 \text{ Ton} \quad (25)$$

Total base cut is

$$V = \sqrt{V_i^2 + V_c^2} = 26 \text{ Ton} \quad (26)$$

The anchor bend below source wall was:

$$h_w = 1.5 \text{ m} \quad (27)$$

$$h_t = 0 \quad (28)$$

$$M_i = C_i [W_i h_i + W_w h_w + W_t h_t] = 32.64 \text{ t} - \text{m} \quad (29)$$

$$M_c = C_c W_c h_c = 6 \text{ t} - \text{m} \quad (30)$$

$$M^* = 61 \text{ Ton} \quad (31)$$

The analysis along Y is the same as along X, because the dimensions of the tank is cubic.

The maximum of the wave height based on journal 123 was:

$$d_{max} = \left(\frac{0.375 C_c}{1 - K_d C_c} \right) D = 53 \text{ Cm} \quad (32)$$

$$K_d = 1.84 \tanh \left(3.68 \frac{h}{D} \right) = 1.84 \quad (33)$$

C: Vertical seismic coefficient of design (regulation 2800)

C_c: Vertical seismic coefficient of design in wavy liquid mode

C_i: Vertical seismic coefficient of design in hard liquid mode

h_i: The mass center height of hard liquid towards the source base at the foot of the wall (without calculation of tank base pressure)

h_s : The height of the tank multi-story base structure which has been measured from the above foundation to the bottom of the reservoir wall.

h_w : The height of the mass gravity center of the reservoir wall towards the tank base in the bottom of the reservoir wall

h_c^* : The height of the wavy liquid mass center towards the tank base in the bottom of the reservoir wall (with pressure entered into the tank base)

h_i^* : The height of the hard liquid mass center towards the tank base in the bottom of the reservoir wall (with pressure entered into the tank base)

M : Total bend anchor in the bottom of the reservoir wall

M^* : Total overturning anchor in the bottom of the reservoir wall

M_c^* : Overturning anchor of wavy liquid mode in the bottom of the wall

V_c : Base cut in wavy liquid mode

V_i : Base cut in hard liquid mode

Three earthquakes of Tabas, Kobe and El Centro have been used under horizontal acceleration to review the damage to concrete. Their information is given in Table 8. Total information related to map acceleration has been downloaded from the site: www.peer.berkej.edu and tame-acceleration charts have been corrected and drawn by SeismoSignal software. They are given in charts 1-3.

Table 8. The information of Tabas, Kobe and El Centro earthquakes

Number	Name	Max. of earth (PGA)acceleration	Effective time duration of the earthquake (s)	Total time t_{total} (s)
1	Tabas	0.835	10.5	32.82
2	Kobe	0.693	6.01	40.95
3	El Centro	0.318	2.02	31.16

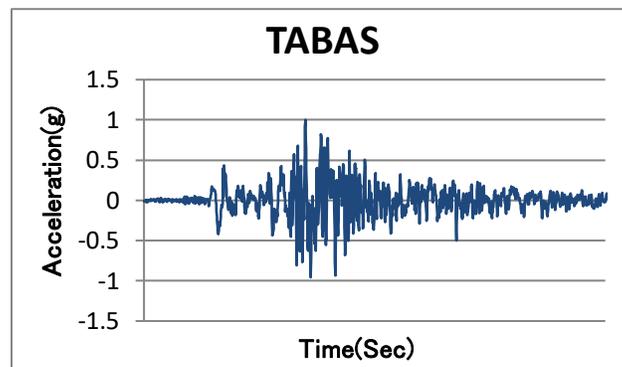


Chart 1. Map acceleration of the Tabas earthquake (acceleration horizontal component)

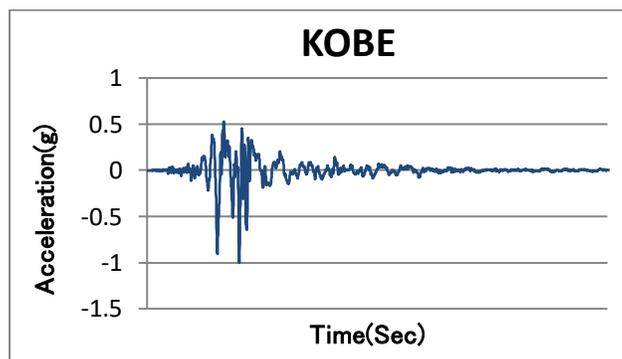


Chart 2. Map acceleration of the Kobe earthquake (acceleration horizontal component)

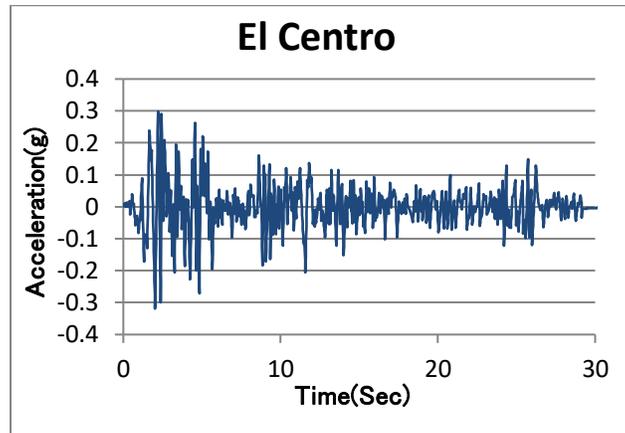


Chart 3. Map acceleration of the El Centro earthquake (acceleration horizontal component)

S4R components (from SHELL family) have been used to review more and compare the desired shell elements to model FRP. This kind of element has been used by many researchers which have provided suitable results.

In the first stage of the analysis, based on the maximum of earthquake forces calculated according to the regulation, forces were applied to the reservoir. There wasn't any damages to the reservoir and the wave height value was obtained 43cm from permissible amount of the regulation. In the second stage of the analysis, the earthquake force was applied to model based on the map acceleration of three earthquakes. The amount of the damage entered into the reservoir was obtained and reviewed. Considering the fact that Tabas earthquake had the maximum of the ground acceleration¹ (the maximum of the ground acceleration is the largest criteria for designing and the main reason for damages when earthquake happens, which is measured by the g (ground gravity acceleration) coefficient), it caused great harm to the reservoir wall. As a result, map acceleration was used to review crack and strength of the reservoir with FRP created by this damage. The results showed that the most damaging was due to compressive stress and water turbulence. This damage had the largest value in the corner of the concrete reservoir. The review of the stress entered into reservoir walls showed that the water wave caused the stress increase of reservoir walls at a rate of 0.76×10^8 . In this research, the analysis of crack growth was done by XFEM method in ABAQUS. It must be used direct cyclic analysis for XFEM method. The concrete crack must be considered oval and its type must be considered SHELL (S4R mesh type).

Before presenting the obtained results of desired tank analysis to validate the model, one of the analyzed reservoirs (its specification is as the same as the modeled reservoir in before studies) has been analyzed (Yazdanian and Fu, 2017). The mechanical specification of fluid and the reservoir of the mentioned paper is given in Table 9 and the outward specification of the concrete is given in Table 10.

Table 9. The mechanical specification of fluid and the reservoir for rectangular concrete reservoirs

Material specification	Type of materials	Density (kg/m ³)	Poisson's ratio	Elastic modulus E(Gp)
concrete	Reinforced concrete	2500	0.2	25
fluid	Water	1000	-	2.07

¹ the maximum of the ground acceleration is the most criteria for design and the main reason for damages when earthquake happens, it is measured by the g (ground gravity acceleration) coefficient

Table 10. The outward specification of the rectangular concrete reservoir

Body thickness (m)	Foundation thickness (m)	Fluid type	Liquid height (m)	Reservoir width (m)	Reservoir length (m)	Reservoir height (m)	Concrete type
0.35	0.40	Water	2.5	11.3	11.3	3	General

The studied reservoir has been done by the horizontal element of the earthquake based on spectrum analysis. Considering the valuation, the maximum of the main tensile stress has been compared due to fluid pressure entered into reservoir wall on that region. The maximum of the tensile stress in this paper and based on the ANSYS software was equal to 1.14×10^6 MPa. This tensile stress has obtained 1.24×10^6 from modelling the same reservoir in ABAQUS software. The maximum of stresses was in the bottom of the walls and above them. The maximum of tensile stress was 1.89×10^6 in this study. Based on the results in this study, the maximum of the wave height has happened to reservoir corners. The force-displacement chart is given in chart 4 which (a) section is related to this study and (b) section is related to the mentioned study. There was a little difference between the figures in the mentioned study and the current study. It is due to insufficient information about armature and reservoir design, the larger dimensions of the reservoir and also use of two different softwares as well as different solvers. So, the results showed the model's validation.

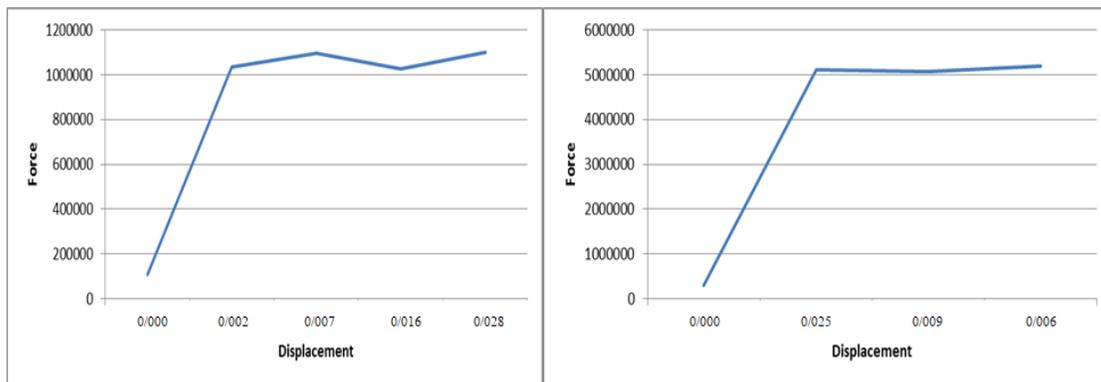


Chart 4. Force-displacement chart (N·m), (a) related to the current study, (b) related to the mentioned study

Also, according to the last study (Mohseni and Bastami) on the behavior of water concrete reservoirs during the earthquake, damages to water concrete reservoirs and their strength have been reviewed after Mormori earthquake and the water reservoir of Dehloran city has been used to confirm the cracks of the reservoir. In this study, numerical modelling of the water concrete reservoir, located in Dehloran city, was done to analyze the mechanical analysis of this reservoir under map acceleration along X and Y. The results of this study showed that damages to walls and roof of the reservoir were in the form of cracks (Mohseni and Bastami, 3rd National Conference on Crisis Management).

Findings

The model of the concrete reservoir was under the map acceleration of Tabas earthquake and had caused damages and cracks to its walls. Spread of the crack was based on before PHILSM² and

² Signed distance function to describe the initial crack front

PSILSM³ and after strengthening. Trend of growth decrease can be found to compare these figures with the primary value of the crack and the face of the crack in wall elements.

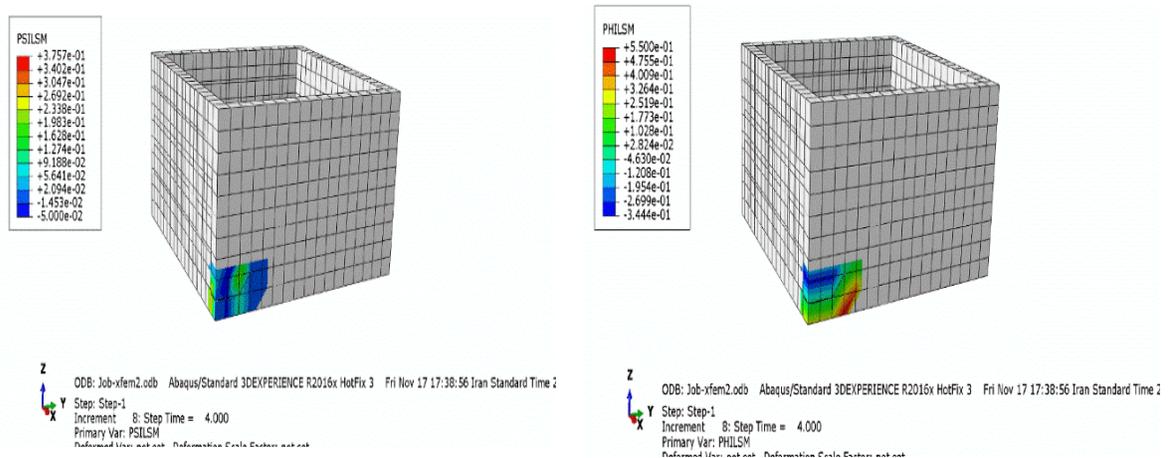


Figure 6. The primary figure of the crack and the face of the crack based on PSILSM and PHILSM after strengthening

The maximum value of the stress was 1.25×10^{13} before strengthening with FRP materials (Figure 8). As it is observed, the stresses didn't suffer from walls, so they caused damages. After placing FRP composite layers on walls, the amount of the stress on them increased. According to Figure 7, the stress number has increased on 1.65×10^{13} . Chart 9 compares the stress with time after and before strengthening with FRP materials for water concrete reservoir. Also, it is indicated that the stress has increased after strengthening. It means that damage and crack needed more stress.

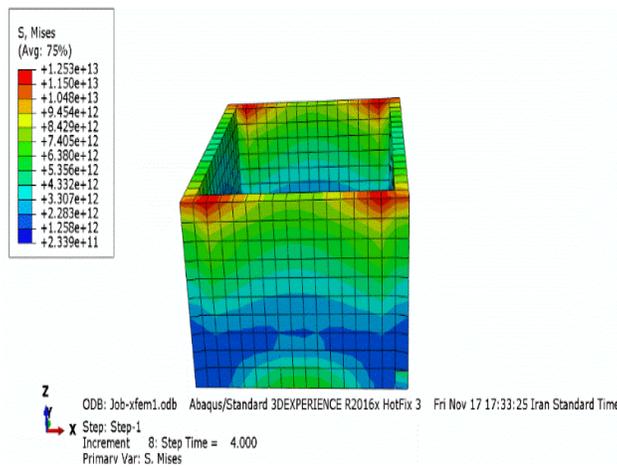


Figure 7. The amount of the stress before strengthening with FRP

³ Signed distance function to describe the crack surface

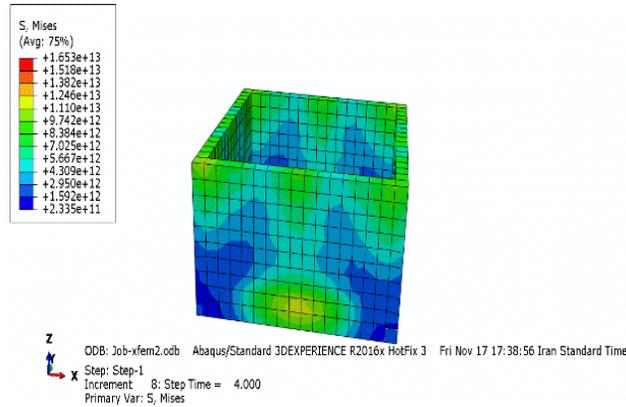


Figure 8. Maximum amount of the stress after strengthening with FRP

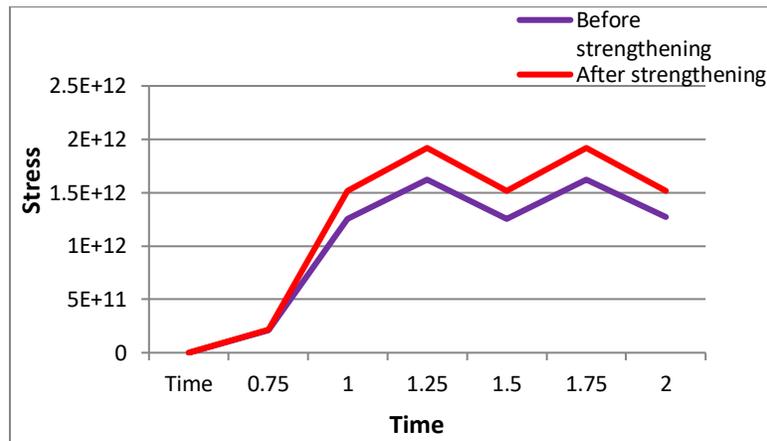


Chart 9. Stress against time before and after strengthening with FRP

The spread of the crack (STATUSXFEM⁴) has come in Figures 10 and 11. This value was one for elements along with crack and zero for elements without any cracks. If elements were cracked partially, the value would be between 0 and 1. According to Figures 10 and 11, the amount of the crack before strengthening, outside the wall, was 100% for destroying 8 elements and 60% for destroying one element. The amount of the crack before strengthening, inside the wall, was 100% for destroying 2 elements and 60% for destroying 2 elements.

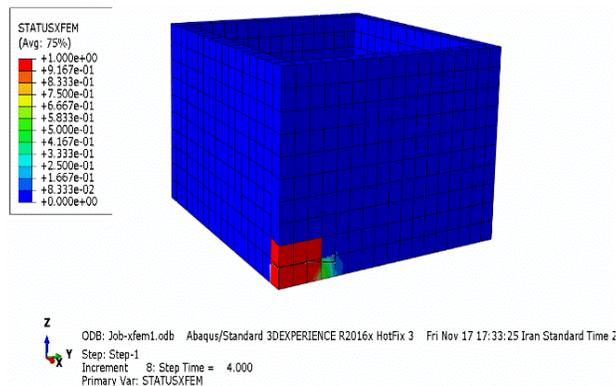


Figure 10. The spread amount of the crack before strengthening outside the wall with FRP

⁴ Status of the enriched element

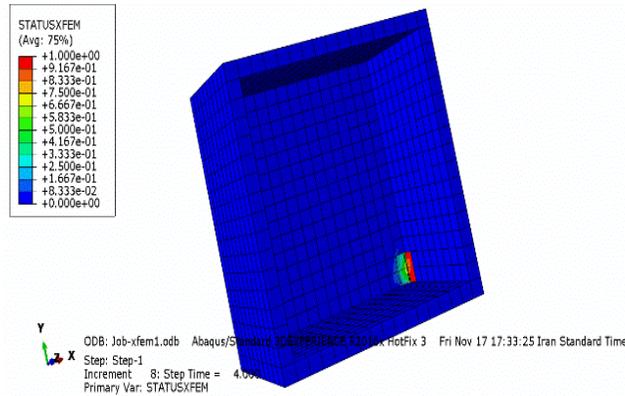


Figure 11. The spread amount of the crack before strengthening inside the wall with FRP

The spread amount of the crack (STATUSXFEM) after strengthening with FRP materials has been shown in Figures 12 and 13. As it is observed, the amount of the crack outside the wall has decreased to 90% for destroying 5 elements outside the wall and 60% for destroying 2 elements inside the wall. It suggests that FRP composites can be used for strengthening concrete reservoirs reliably.

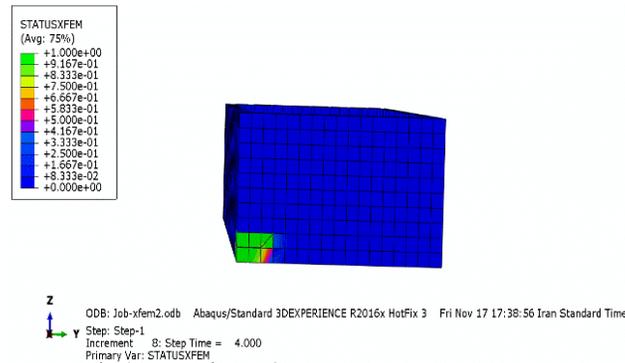


Figure 12. The spread amount of the crack after strengthening the reservoir with FRP outside the wall

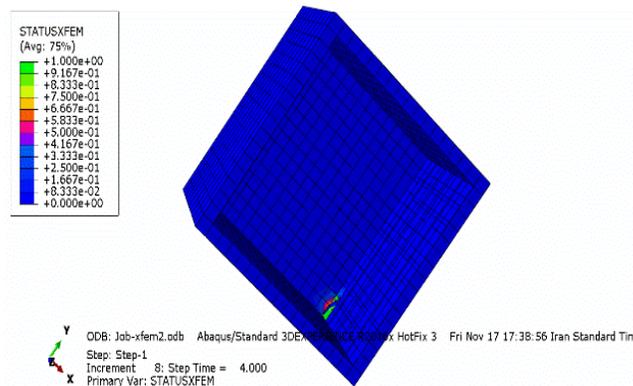


Figure 13. The spread amount of the crack after strengthening the reservoir with FRP inside the wall

After modelling the water underground concrete reservoir using the ABAQUS software and careful mesh of elements and the exertion of earthquake force at the maximum of the ground acceleration (PGA), the amount of the damage to reservoir walls was considered. So, the maximum damage to reservoir was related to the damage induced by compressive stress due to water wave forces. After

strengthening with FRP materials, the amount of the tolerable stress increased in reservoir and the spread of the crack decreased in cracked region. It showed the correct performance of FRP materials in strengthening and decrease of damages induced by the earthquake to concrete reservoirs above the ground.

CFRP composites with bidirectional fibers were used for strengthening the walls of concrete reservoirs above the ground. The thickness of their sheets were 1.5 mm.

According to the placement of the FRP composites above the reservoir wall, the kind of the CFRP composites and their placement must be inside the reservoir and start from the bottom of the wall. The main side of composite fibers must be along cracks and considering the reservoir height, it must be 3m. The width of composite rolls was 50cm in 6 rows for each wall. The installation stages of FRP composites have been mentioned that are necessary for the improvement and performance of FRP composites.

Conclusion

The obtained results of non-linear analysis of the water concrete reservoir and stress values, after strengthening underground concrete reservoir, showed very reliable and suitable criterion to understand how to strengthen the studied reservoir with CFRP polymer fibers.

- The more the earthquake (PGA) happened, the more the results such as base cut, displacement and wave height of the reservoir increased. The largest stress was in the corner and bottom of the walls in rectangular reservoirs.
- In fact, because of the dominance of hydrodynamics forces, water sounded in concrete reservoirs above the ground. The disadvantages of these reservoirs were merely side-walls. Other elements of water reservoirs didn't get any damage, because water hydrodynamics forces didn't enter into them. So, it is proposed that CFRP polymer fibers can merely be used for strengthening water reservoirs to decrease cost in side-walls.
- FRP sheets were able to improve performance level of the armature concrete reservoirs.
- FRP sheets led to an increase in the stiffness and load capacity of the concrete reservoir above the ground.
- ABAQUS software was able to do non-linear analysis of concrete reservoirs and the obtained results from experimental experiments and their comparison with software outputs confirmed this claim.
- Using the XFEM method was very carefully done and was effective for analysis and spread of the crack. So this method was more suitable than other existing methods.

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