Seismic Performance of Eight Elevated Water Tanks During Silakhor, Iran Earthquake of 31 March 2006

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ABSTRACT :
Many of elevated water tanks damaged during an earthquake occurred at 31 of March 2005 in Silakhor, Iran. In this study, the seismic performance of eight elevated water tanks have been evaluated qualitatively and .three of them have been studied analytically. Based on a detailed survey, the following modes of failure are recognized: (1) Buckling of the slender bracings due to compressional stresses, (2) Failure of the turnbuckles, (3)Brittle failure of the vertical bracings, (4) Rupture of the bottom plate of the tanks in vicinity of the joints of the supporting structure elements, (5) Formation of plastic hinge (hinges) in one of the top beams in the supporting structure, (6) Failure of joint wildings of the pipes, connected to the end of shaft, which cause the water in the tank to run off. A force-based method based on the Iranian Seismic Code (ISIR 2800) is employed to evaluate the components of three elevated tanks. A performance based design approach has been used to verify the results. A performance factor is calculated through nonlinear analyses which are related to performance based methods. The results of this study show that the force based method fail to estimate accurately the capacity of these structures including the nonlinear behavior of the elements. Nevertheless, a more convenient method for designing elevated tanks such as a performance-based seismic methodology is needed. Moreover, if the force methods are applied for designing new tanks the response modification factor (R) must be reduced from 3, according to the Iranian Seismic Code (ISIR 2800) to 2.

KEYWORDS:
Elevated Water Tanks, Seismic Performance

1. INTRODUCTION

According to international seismology and earthquake engineering center, an earthquake was recorded for the south of Brujerd (covering 330 villages in Dasht Darbastaneh in Silakhor region between Brujerd and Durood) and the reported data is as follows:

The main quake at 4:47 a.m on 3.30.2006.
A prequake at 7:47 p.m. on 3.29.2006 with 4.6 ML
Another prequake at 11:06 p.m. on 3.29.2006 with 5.1 ML
The post quake at 5.01 a.m on 3.30.2006 with 4.9 ML

Chlanchulan region near Brujerd was reported as the main destroyed area. There were a lot of elevated water tanks for rural, urban and industrial use which were damaged by the earthquake. The water tanks are about 11-30 meter high with 10-125 m^3 capacities. They had been designed base force method the same as other normal building and tanks. The figure 1 shows the position of tanks. Figures 2 show the recorded acceleration in the vertical direction from the nearest seismologic station (chalan chalan station) to the center of the earthquake.

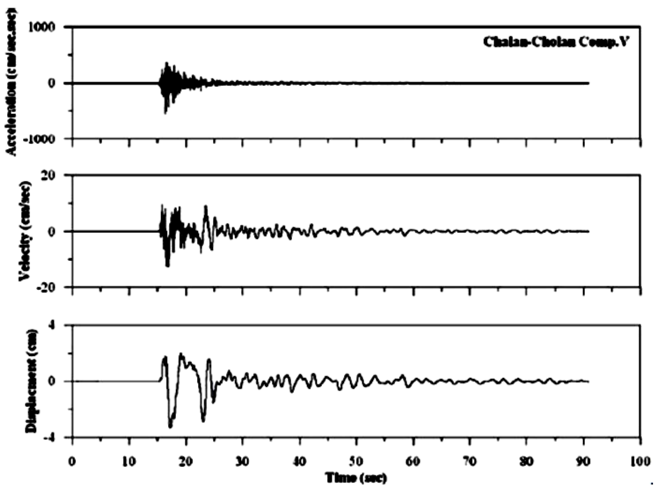

Figure 2: the recorded accelerations in chalan chulan station in Brujerd comp (V).

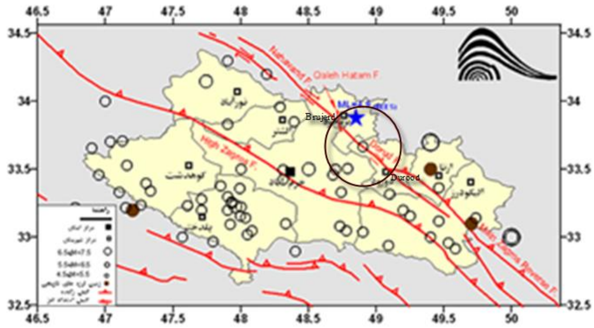

Figure 1: the locations of the studied water tanks in Brujerd.

2. THE STUDIED WATER TANKS

The studied water tanks include the existing water tanks in Shahid Chamran, Imam Khomeini and Kosar (tow tanks) hospitals all situated within Brujerd urban region, as well as, the elevated water tanks of Ghorehsoo, Silakhor (chaman chalan chulan) and Babapashman villages and the yeast production plant water tank.

All qualifying assessment were performed over those water tanks and then Shahid Chamran. Hospital, Babapashman village and the yeast production plant water tanks were selected as the most damaged water tanks to be performed the quantifying assessments. Table 1 shows their characteristics.

Table 1: the studied elevated water tanks characteristics

				Type of Profile			
Elevated water tanks	Height (floor tank)	Storage capacity (m3)	Liquid volume (m3)	Column	Beam	Brace	Horizontal Brace
Kosar hospital **(tank1)**	25.4	49	24	Double channel14,6,0.7	Box B= 8cm	Φ25	Box B= 8 cm
Kosar hospital **(tank2)**	10.6	11.5		Pipe D= 11 cm	Pipe D= 7 cm	Φ15	Pipe D= 2 cm
Chamran hospital	11.6	40	20	Box B= 14 cm	Pipe D= 7 cm	Φ15	Pipe D= 2 cm
Imam Khomeini hospital	14.2	34.5		Box B= 13 cm	Pipe D= 8 cm	Φ15	Pipe D= 2 cm
Gharehsoo village	11.4	32		Pipe D=16cm	Pipe D=11 cm	Φ20	Φ20
Silakhor village	16.4	105		Pipe D=25 cm	Pipe D= 12cm	Φ25	Φ20
Baba pashman village	10.5	23.5		Pipe D=15 cm	Pipe D= 8 cm	Φ15	-
yeast production plant	30	125		Double channel20,75,0.85	18,7,0.8 ناودانی	Φ30	Box B=10cm

3. QUALIFYING ASSESSMENT OF THE WATER TANKS VULNERABILITY

The damages to the pre mentioned water tanks include

- The disruption of very slender brace used in these structures due to their inability to resist against the compression and fats bucking.
- The disruption of the turnbuckles used in the braces.
- The disruption of the vertical brittle brace.
- The tank floor pulling a part where it joins to the beam and columns due to very displacements of the beams and columns of the water tank structure support.
- Formation a plastic joint in one of the beams, at the highest level of the water tank structure.
- The disruption in the welded joint of water pipes where they attach to the shaft and because of lack of enough free movement when the water tank is largely displaced, the event that led to water tank draining when the earthquake occurred.

The figures below show the damages:

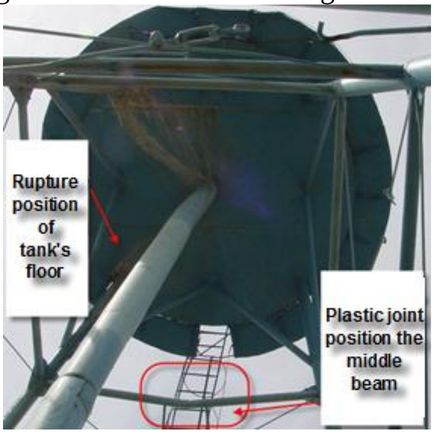

Figure 3: Some damages in the support structure and the water tank of Babapashman village.

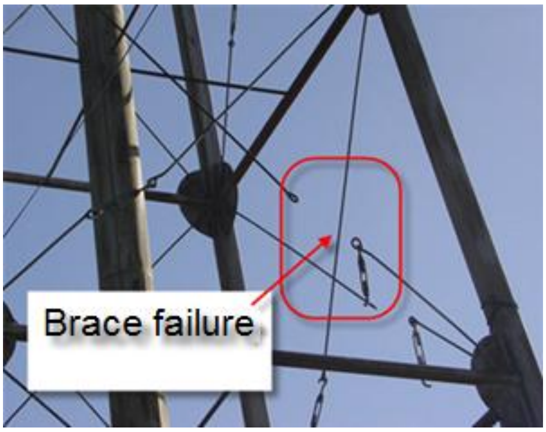

Figure 4: The disruption of the turnbuckles used in the braces in Chamran hospital water tank.

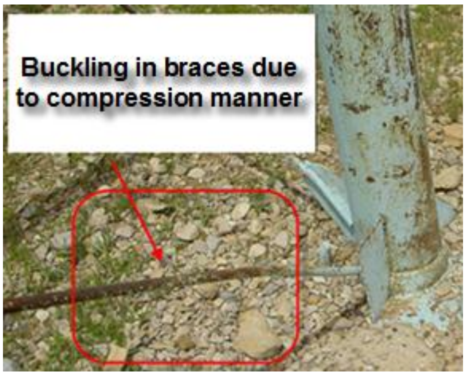

Figure 5: Babapashman village water tank structure.

Figure 6: The brittle failure of turnbuckles in the brace of Silakhor village water tank.

4. THE WATER TANKS DAMAGES QUANTITIES ASSESSMENT

4.1. The structure modeling

Elevated water tank structures are mostly considered as having regular configuration. The forces in the structure are distributed almost uniformly. There are similar lateral resistances in the columns due to their shear fixed position. The structure mass is mostly on top of the tank when it is full or semi full.

The findings from previous earthquakes show that above ground metal tank itself rarely suffers from earthquake damages because of its floor and wall thickness, enough to resist water content lateral forces when it is loaded by gravitation or by earthquake movement. Therefore, considering the above fact as well as other factors such as complexity of modeling water mass in terms of tow cases, that is, impulsive and connective modes and elasticity elements inclusion in order to demonstrate connective mass impact, consequently led to consider the structure parts as sufficient for modeling. The water tank weight and its water content impact and water turbulent force

because of earthquake are included in the model. It was also attempted to keep the same equal displacement and rotation at column ends because of solid performance of tank floor diaphragm affecting on the structure as much as possible. Due to the lack of ‘as build’ maps and structure design and irresolvable questions such as how the clamping acts on the ground, both clamping and not clamping are considered in the measurement.
Chandrasecaran and Krishna relations are used to assess impulsive and connective masses of liquid and their impact location on the tanks in order to measure tow order freedom system equivalent of the tank and its liquid content (figure 7). M_e and K_1 refer ti connective mode and are similar to the modified version of Housner’s given by Ashraf Habibollah and Wilson, M_i. Refers to impulsive mode which include water mass connected to the tank storage (M_i) and the tank and its support structure masses.

$$Mc = M(.71)\frac{\tanh 1.8h/R}{1.8h/R} \quad (1)$$

$$T\omega = 2\pi\sqrt{\frac{Mc}{Rl}} \quad (2)$$

$$Mi = M\frac{\tanh 1.7R/h}{1.7R/h} \quad (3)$$

$$hi = .38h\left[1+\alpha\left[\frac{M}{Mc}-1\right]\right] \quad (4)$$

$$Ki = 4.75\frac{Mc^2}{M}\frac{gh}{R^2} \quad (5)$$

$$hc = h\left[1-.21\left(\frac{M}{Mc}\right)\left(\frac{R}{h}\right)^2 + .55\beta\frac{R}{h}\sqrt{0.15\left(\frac{MR}{Mch}\right)^2-1}\right] \quad (6)$$

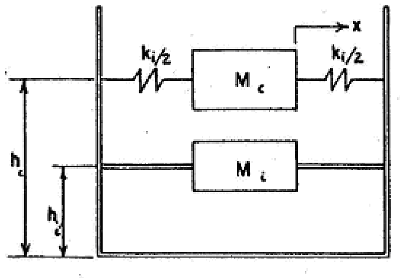

Figure 7: Tow order freedom system equivalent to the tank and its liquid content.

5. THE EXISTING CODE OF SEISMIC DESIGN OF ELEVATED WATER TANKS

At the present all codes which refer to earthquake design of above ground tanks are based on force methods and yet performance based design on the tank is not used practically.
The most important codes are:

a. AWWA D-100 (1996), AWWA D-103 (1997), AWWA D-110 (1995) and AWWA D-115 (1995).
b. API 650 (1998)
c. Eurocode (1998)
d. NZSEE guide lines & NZS 4203: 1992

There are two ways to assess the structure behavior and to design its components in force methods: Linear and nonlinear methods. However, linear analysis of structure is a normal method to be performed for steel structures. There is no code for elevated water tanks in Iran except for underground tanks including some limited sections covering the load measurement with Seismic considerations and some important controls such as overturning , etc.
It should be noted that in addition to what mentioned in modeling section, AISC codes and article 10 in national codes of building in Iran refer to steel structures and is based on allowable stress are used.
According to this procedure, first gravitational and seismic loads over the structure are measured, then these loads are added to the structure design with certain coefficients, and the resulted stress in the structure are compared with their allowance. Souedynamic static analysis is normally used for linear analysis of structure to measure seismic load for the structure. First parameters of designed base acceleration, reflection coefficient of structure and its importance are used to measure the seismic force and then resulted force is reduced by using a coefficient called “structure performance coefficient”.
Clearly, structure components behaviors are not considered when designing and controlling them and all components are reduced equally.
Recently performance – based designing is on focus. It is mostly used for proper approximation of structure response for Seismic load. Rather, we can use displacement control methods for design purposes to improve the design and have an insight on the structure performance. However, normal ways of designing such as allowable stress or load coefficients and resistance , were the only parameter of structure behavior control.
If is explicated for structure modeling the support structure components inclusion is sufficient. The tank weight

and its water content weight and seismic force based turbulent mode parameters are added to the model after some handy measurement based on the prementioned relations. Then the model becomes similar to a building frame, to which performance based design principles are applicable in order to control the tank structure components. Thereafter, we need to consider such problem as analysis method selection and various regularities. First we perform simple analysis and get the results and then explore the acceptance criterions for the components according to existing structure improvement guide lines and Fema 356.

6. TO COMPARE DCR AND ACC VALUES TO ALLOWABLE STRESS RATES IN CODE-BASED METHODES

Acceptance criterion values (Acc) and demand-capacity ratio (Dcr) for the structure components are determined considering the liquid modes and structure supports. The level of components acceptance in performance-based design is limited, mostly because of using higher forces rather than allowable stress.

In static equivalent trend for determining forces based on allowable stress methods, performance factor for elevated water tanks is 3, the same value as present codes determine.

This reduces force in static equivalent method. However, there are other factors as well. For instance, structure importance index is used in static method which increase the forces imposed on the structure.

Oversight to expectable performance of structure (immediately occupancy of the tanks) in the allowable stress method is a key factor of the resulted forces decrease. In these structures importance index is the only factor to be considered in structure performance, the trend which leads to some losses and faults due to not caring to controllability of structure component behavior by displacement or force. On the whole, this leads to face higher forces in performance-based design. Another fault in allowable stress method is structure component inclusion into nonlinear behavior area.

This is clearly shown when comparing component acceptance level in tow methods of performance-based control and allowable stress-based control. Due to definitions for structure performance factor is shown that we can take either structure falling performance or it’s immediately occupancy performance in order to determine performance final point performance factor in regard to base shear or displacement. However, the point is that we do not encounter force final value and displacement when various earthquakes impose their forces. Actually it is reduced or increased. For example when Babapashman water tank encounters less forces, The problem is that the structure has not proceeded such that we can reduce the existing forces in the structure the same as determined performance factor reduction. There force, if so, we would encounter components which have got expectable ratio of existing stress to allowable value under the relative controls of allowable stress. But which performance-based controls, they get higher acceptance level and would not satisfy acceptance criterion and they would need improvement.

Also note that the acceptance level is compared in various methods. Uniform reduction rate or increase rate of component acceptance level based on allowable stress control or performance happens in joint support or clamped methods, which indicates the validity of the results.

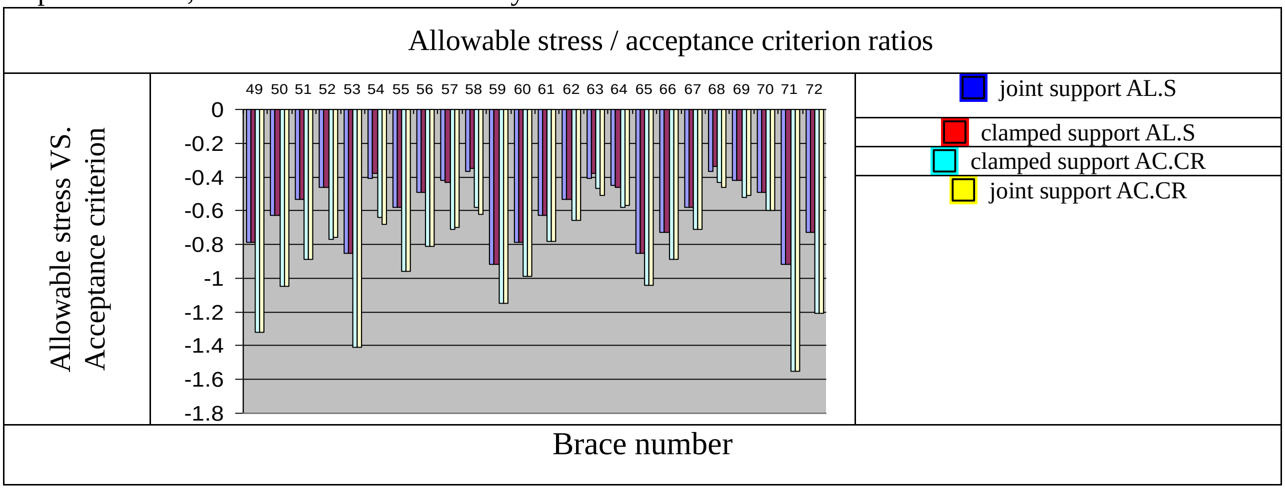

Figure 8: Comparing ACC rates with allowable stress of braces in half full mode for the yeast production plant.

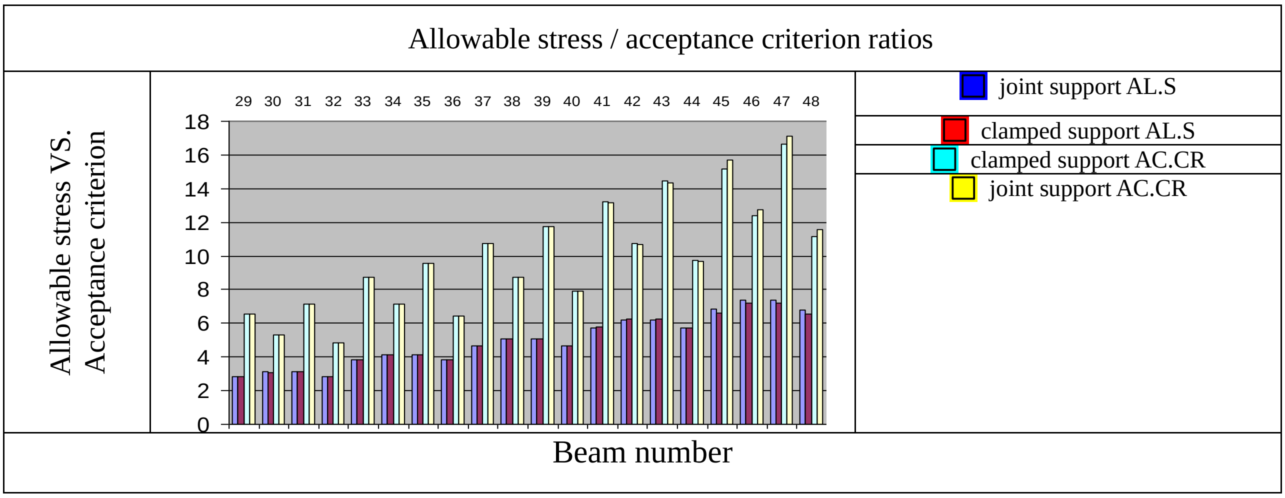

Figure 9: Comparing ACC rates with allowable stress of beams in half full mode for yeast production plant.

7. PERFORMANCE FACTOR MEASUREMENT

Performance factor for the support structure of the tanks were measured using Krawinkler relations. We needed to include result of nonlinear behavior analysis of the tanks.

One of functions of structure performance factor measurement is to illustrate structure proceeding rate in nonlinear behavior area. In this section, the measurements have been performed for tow performance modes. First, it is measured for the time the structure is going to fall and there is a significant load loss. Then, it is measured for the immediately occupancy performance the acceptance criterion for this performance related to the structure components is based on controlling effort according to FEMA in the structure nonlinear analysis consideration.

The needed designed load for performance factor measurement was determined according to code 2800, the third version and using connective and impulsive modes of tank liquid content. Other data was necessary such as the imposed load and displacement when the first joint forms and maximum displacement and Base shear of the structure coming from nonlinear analysis.

After each nonlinear analysis, Base shear curve versus lateral displacement of control node (as the center of gravity the highest level of structure) is drawn. Now, we can deal with the structure performance factors. In table 2 and 3, the measurement is given for Babapashman village tank in full mode with joint support.

Table 2: the nonlinear behavior of Babapashman water tank structure in full mode with joint support and considering immediately occupancy performance.

Maximum Base shear of structure in nonlinear static analysis (kg)	**10860**	Maximum displacement of structure in static nonlinear analysis (cm)	**3.67**
Base shear in yield point of first plastic joint of structure. (kg)	**9240**	Structure displacement in yield point of first plastic joint of structure. (cm)	**2.24**
Designed Base shear of structure. (kg)	**7715**		

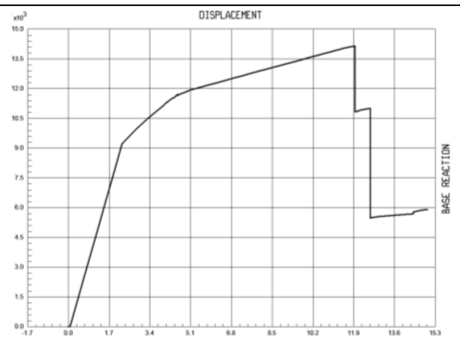

Figure 10: nonlinear behavior curve of the structure of Babapashman village tank in full mode and joint support by using static push over analysis in X , Y directions with Gravitation load of G1.

Rs1	**1.20**	**Rs2**	**1.18**
μ	**1.64**	**T**	**0.475 s**
Rμ	**1.62**	**C(T,α)**	**1.1**
R	**2.28**	**a(α=2%)**	**1**
		b(α=2%)	**0.37**

Table 3: performance factor measurement for Babapashman water tank structure in full mode with joint support and considering immediately occupancy performance.

8. CONCLUSION

8.1. Quality measurement

- Improper quality of design and construction of the tanks were evident. We faced significant damages in the tank which was described in the related section.
- An interesting case was using of lateral loading of the braces which are able only to resist tension to which most damages to tanks are attributed. In this case all lateral loads are allocated to the tensional brace and its compressional manner is ignored. Since the very slender braces of structure is quickly buckled by a little compress, the diagonal braces would behave properly in cyclic loads and seismic load if they have both tension yield and suffer compressional nonlinear buckling and show a nonlinear behavior. This happens for the relative slender braces ($80<\lambda<110$) and unfortunately the very slender braces don't suffer from nonlinear behavior in compressional behavior and don't spend energy in response to the seismic load suitably, which is evident from their hysteresis curve.

8.2. Quantity measurement

- The structure behave similarly in clamped and joint modes of connection to the ground and the braces used in structure ports, it is indicated that they mostly behave as a truss. The evident to this behavior are: little rotation of support in joint mode, structure displacement being similar to shear deformation in both joint and clamped modes. However, this holds before mechanism happens in various parts of structure.
- Water content quantity in the tanks while the earthquake happens is very important. Unfortunately proper maintenance are not done to the water content, especially in villages, for example if they are designed for half full mode, they will suffer damage if used improperly in full mode, since the structure would carry some extra forces.
- Lateral load-capacity disagreement in present thanks in their full mode creates improper condition. Additionally, similar to the ground tanks, some issues such as not to be enough liquid free height imposes problems for the structure and the tank wall and its floor may be buckled.
- Performance-based design limits member acceptance level in structure control.
- Allowable stress-based design used static equivalent method to determine forces and performance factor was 3 for elevated water tanks. The same value is common for structure behavior factor in other countries codes and it is a decreasing factor in static equivalent method.
- Oversight to expectable performance of structure (immediately occupancy of the tanks) in the allowable stress method is a key factor of the resulted forces decrease. In these structures importance index is the only factor to be considered in structure performance, the trend which leads to some losses and faults due to not caring to controllability of structure component behavior by displacement or force. However, in performance-based methods, structure components are permitted to behave limited nonlinearly i respect to whether their behavior is controlled by displacement or force.
- Another fault in allowable stress method is structure component inclusion into nonlinear behavior area. When we compare tow methods of performance-based control and allowable stress-based control for acceptance level of component. We observe that some components have got acceptable existing stress to allowable stress ratio but they also get higher acceptance level with performance-based controls and they don't satisfy acceptance criterion, so they must be improved.
- Another flaw is that performance factor in structure design is measured for final point of performance in respect to base shear and displacement. But the point is that we don't have exactly final force and displacement and we may face with less or more value rather than the final.
- The components acceptance level for the tanks are equal on performance-based and allowable based controls in tow modes of joint and clamped supports.
- The main part of extra resistance in support structure of the tanks is due to columns bendig and double behaviors of the structure while the braces yield as well as more resistance of columns against the imposed loads than other components of the structure.
- Performance factor of 2 can be proposed for elevated water tanks in immediately occupancy mode performance if they are designed properly.

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