Performance of elevated tanks in M_w 7.7 Bhuj earthquake of January 26th, 2001

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The current designs of supporting structures of elevated water tanks are extremely vulnerable under lateral forces due to an earthquake and the Bhuj earthquake provided another illustration when a great many water tank stagings suffered damage and a few collapsed. The more popular shaft type stagings suffer from poor ductility of thin shell sections besides low redundancy and toughness whereas framed stagings consist of weak members and poor brace-column joints. A strength analysis of a few damaged shaft type stagings clearly shows that all of them either met or exceeded the strength requirements of IS:1893–1984, however, they were all found deficient when compared with requirements of the International Building Code. IS:1893–1984 is unjustifiably low for these systems which do not have the advantage of ductility and redundancy and are currently being underestimated at least by a factor of 3 and need an upward revision of forces immediately.

1. Introduction

Many elevated water tanks suffered damage to their staging (support structure) in the M_w 7.7 Bhuj earthquake of January 26th, 2001 and at least three of them collapsed. These water tanks are located in the area of a radius of approximately 125 km from the epicenter (USGS). The majority of these tanks are supported on cylindrical shaft type staging which developed circumferential flexural cracks near the base. RC framed stagings are not very common for elevated tanks in this part of the country. Two of such tanks located in regions of the highest intensity of shaking collapsed while a few developed cracking near brace-column joint regions. Critical facilities like water tanks, therefore require careful scrutiny of their designs, especially those far away from the epicentral tract and located in the areas which experienced shaking of MSK intensity IX and VIII. Even in the regions of the highest shaking of intensity X, these structures should not have collapsed. They are expected to remain functional even after the occurrence of a design level earthquake.

2. Damage observed to elevated water tanks

Hollow circular shaft is the most popular type of staging to support a tank container. The height of the shaft varied from a minimum of about 10 m to a maximum of 20 m whereas the shape and size of the tank container largely depended on the storage capacity and required head for the water supply. The affected tanks varied in their storage capacity from 80 kL to 1000 kL. The diameter of the staging generally increases with increase in the capacity of the tank, however, the thickness of the staging section is usually kept between 150 and 200 mm. The flexure cracks in stagings were observed from the level of the first "lift" to several lifts reaching one-third the height of the staging, as shown in figure 1. These cracks are mostly in a circumferential direction and cover the entire perimeter of the shaft. They usually appear near the edges of the form used during casting of the shaft, which appear to form planes of weaknesses along the shaft's length. These cracks pass through the thin section of the staging and are clearly visible from inside too (figure 2).

Keywords. Elevated water tanks; staging; shaft support; reinforced concrete; earthquakes; damage.

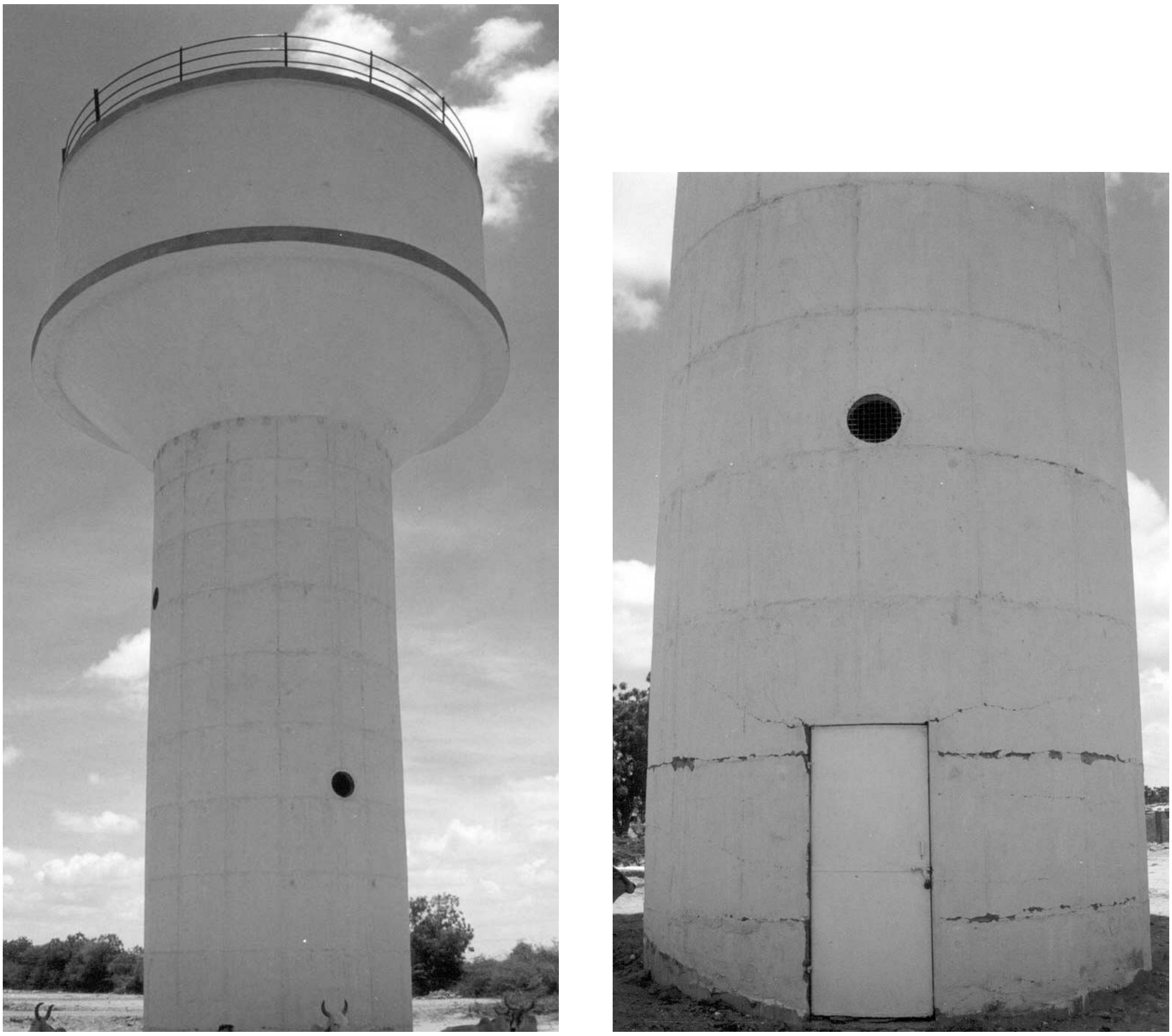

Figure 1. 200 kL Bhachau water tank which developed circumferential cracks up to one-third height of the staging. Severe cracking at the junctions of the first two 'lifts'.

The elevated water tanks are inverted pendulum-type structures which resist lateral forces by the flexural strength and stiffness of their circular hollow shaft type staging. The section close to the ground is subjected to the maximum flexural demand. Any damage to the staging at this critical section should be considered alarming as it can seriously undermine its lateral load-carrying capacity. However, most of these tanks are being used as before. In a few cases, for example, the water tank in Darbar Garh, Morbi was repaired by injecting epoxies in the cracks, as shown in figure 3. The observed damage pattern is consistent with the expected response of these structures under lateral loads. While many water tanks escaped the earthquake with minor to severe flexural cracks, the water tank in the village Chobari in the epicentral tract did collapse (figure 4).

3. Frame type staging

Frame type stagings are generally regarded superior to shaft type staging for lateral resistance because of their large redundancy and greater capacity to absorb seismic energy through inelastic actions. Framed stagings have many flexural members in the form of braces and columns to resist lateral loads and damage to a few will not result in the sudden collapse of the structure as inelastic deformations and damage is distributed to a large number of frame members. Furthermore, such RC frameworks can be designed to perform in a ductile fashion under lateral loads with greater reliability and confidence as opposed to thin shell sections of the shaft type staging. The sections near the beam ends can be designed and detailed to sustain inelastic deformation and dissipate seismic energy.

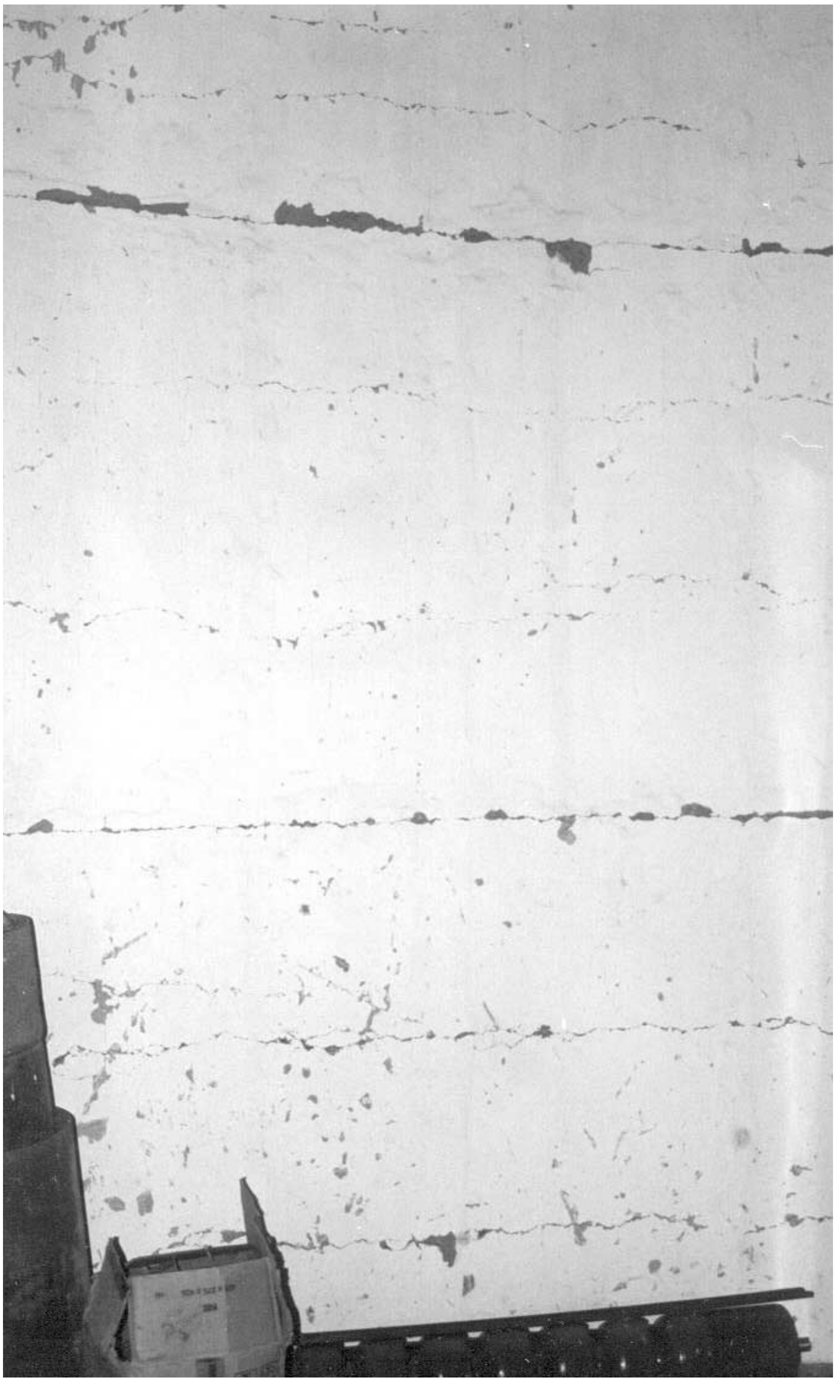

Figure 2. Cracks are 'through' the shell thickness as seen from inside the shaft of 1000 kL Anjar Nagar Palika Tank.

However, if the frame members and the brace-column joints are not designed and detailed for inelastic deformations, a collapse of the staging may occur under seismic overloads. Tank staging in Manfera village (figure 5) in the epicentral tract collapsed whereas severe damage to a tank in Bhachau warranted it to be torn down. Clearly, brace and column members of tanks in Manfera and Bhachau do not meet the ductility and toughness requirements for earthquake resistance. Figure 6 shows disintegrated brace-column joints of the collapsed staging which is poorly detailed even for non-seismic moments. Termination of longitudinal bars in the joint region, 90° hooks for insufficient number of stirrups and poor quality of concrete are some obvious omissions leading to the failure of joints and eventually causing the collapse of the supporting frame. The collapse of the structure could have been prevented if the frame members of stagings were detailed according to provisions of IS:13920-1993 (BIS 1993a) and IS:11682-1985 (BIS 1985) which

Figure 3. Flexural cracks in staging of 500 kL tank being repaired by injecting epoxy. This tank in Morbi, 80 km away from the epicenter, was empty at the time of the earthquake.

refers to the ductility requirements of IS:4326-1976 (BIS 1976).

4. Lateral strength of shaft type stagings and review of code seismic design forces

As shown in figure 7 due to lateral seismic forces on tank structures, the maximum moment occurs at the base of the staging and for circular shaft type staging the points on the outer fibers of the staging section are subjected to maximum bending stress. The critical stress for design is obtained by combining this maximum bending stress with the uniform axial compression stress due to the weight of the tank structure. For the section to crack, it is necessary that the combined stress at outer fibers exceeds the tensile strength of the concrete, $f_{\rm cr}$. Assuming thickness of staging t to be much smaller in comparison to the radius of staging r, and ignoring the small percentage of shell reinforcement, the expression for the moment which will cause cracking, $M_{\rm cr}$, can be obtained by equating combined stress at outer fiber to the tensile strength of concrete, i.e.,

$$-\frac{\gamma P}{2\pi r t} + \frac{M_{\rm cr}}{\pi r^2 t} = f_{\rm cr} \tag{1}$$

where, P is axial load and γ is the appropriate load factor. Taking $f_{\rm cr} = 0.7\sqrt{f_{\rm ck}}$ MPa, where $f_{\rm ck}$ is

Figure 4. Collapsed 265 kL water tank in Chobari village about 20 km from the epicenter. The tank was approximately half full during the earthquake.

characteristic strength of concrete, the above relation can be used to give the cracking moment of resistance $M_{\rm cr}$ of the staging section. Estimate lateral shear strength $V_{\rm cr}$ corresponding to the cracking moment resistance $M_{\rm cr}$ can be obtained using a simplified single degree of freedom representation for the elevated tank structures.

In figure 8, the available shear strength in stagings of the affected tanks is compared against the lateral strength required by IS:1893-1984 (BIS 1984) in the Seismic Zone V, the highest seismic zone in which most of the affected tanks are located. For a sample of eight tanks, the provided lateral strength against tensile cracking of staging was either equal or larger than the code required strength and maximum overstrength being as large as 170%. In other words, the stagings do meet or exceed the strength requirements of IS:1893-1984. However, they will be considered seismically deficient due to inadequate lateral strength capacity by International Building Code (IBC 2000) under similar seismic exposure conditions.

It is interesting to note that structural designs of eight water tanks with such large variations in their capacities (from 80 kL to 1000 kL) are such that they are all short period structures for earthquake loads except the one at Gala subhead water works. Consequently, the overall seismic response of these structures is most directly related to accelerations of the ground motion and will not be greatly affected by the yielding and ductility of the supporting structure. Providing a sufficiently large lateral strength is probably the most effective way to ensure protection against ultimate earthquake loads. Further, sections of very thin cylindrical shells do not possess any appreciable level of ductility (Zahn 1990; Rao 2000). As a result, for such structures, on account of ductility the design forces can not be reduced below those which would be developed if they are to remain elastic during an ultimate event. Consequently, the reduction in design forces specified by various codes because of inelastic behavior or ductility is significantly small for such structures in comparison to building structures. The small reduction in design forces is also partly due to the little redundancy present in such structures, i.e., one plastic hinge in a staging can cause collapse of the structure. As a result, most advanced codes such as 2000 IBC specify design forces for such cantilevered pendulum type structures about 2 to 3 times of those intended for building structures. However, in contrast to 2000 IBC, the design forces prescribed by IS:1893-1984 are essentially at the same level as specified for the most ductile moment resisting frames for building structures. The resulting forces are unjustifiably low for structural systems which do not have advantages of redundancy, ductility and toughness. If the affected tanks were provided only the code level strength, the damage would have been more severe, possibly threatening the lateral stability of the entire structure.

(b)

(a)

Figure 5. **(a)** Collapsed slender and weak framed stagings of water tanks in Manfera village. **(b)** Severe damage to similar staging required that the water tank be pulled down in Bhachau.

Figure 6. Poor detailing of column-brace joints for Manfera tank.

An ultimate strength analysis of the staging section of the collapsed Chobari water tank is carried out which involved the calculation of ultimate direct force and ultimate bending moment that can be resisted by the resulting stress envelope. The envelope of resistance is presented in the form of an interaction plot with the moment as the abscissa and axial load as the ordinate. The strength interaction curves were developed corresponding to factored strengths and nominal strengths as per IS:456–2000 (BIS 2000). Geometrical and material parameters used to derive the resistance envelope were:

- Mean radius of section $r = 2.25\,\mathrm{m}$,
- Shell thickness $t = 160\,\mathrm{mm}$,
- Ratio of longitudinal steel to gross section = 0.00283,
- Angle subtended by door opening at the center of the section = 0.44 rad,
- Cube strength of concrete $f_{\mathrm{ck}} = 20\,\mathrm{MPa}$, and
- Yield strength of reinforcement $f_{\mathrm{y}} = 415\,\mathrm{MPa}$.

To assess the safety of the structure, the available capacity at the critical section is compared with probable demands specified by IS:1893-1984. The 'open' and 'filled' circles in figure 9, represent factored seismic demand for empty and full tank cases according to the two critical load combinations. It is clear that the staging of Chobari water tank was probably safe for seismic forces specified by IS:1893-1984, if we ignore the possibility of poor quality construction which can not be ruled out considering its remote location. In other words, the seismic forces were indeed larger than code specified forces on the morning of the earthquake when the tank was about half full. A low seismic design force results in low flexural demand from the staging section which encourages slender stagings with thin shell sections. It is clear that damages observed in stagings of elevated water tanks once again illustrate that the IS:1893-1984 design forces are currently being underestimated by at least a factor of 3 and need an upward revision of forces immediately. In an earlier study Jain and Sameer (1993) have also pointed out this deficiency of IS:1893-1984 and advocated that the forces be increased by increasing the performance factor for elevated water tanks to 3 from the current value of 1.

5. Conclusions

The current designs of RC shaft type circular staging (supporting structure) for elevated water tanks are extremely vulnerable to lateral loads caused by earthquakes. It is evident from the damages sustained to stagings as far as 125 km away from the epicentral tract of the Bhuj earthquake. This is despite the fact that most stagings could withstand the seismic forces greater than those specified by IS:1893-1984.

The supporting structure, especially the framed stagings may look like that used in the building-like structures but its behaviour under seismic loads is very different. Moreover, the staging does not have much redundancy and hence toughness – a desirable feature for earthquake-resistance – which is typically present in the multiple bays and framelines of a building framing system. This lack of redundancy is extremely serious in circular shaft type staging where lateral stability of the structure depends on only a single element, i.e., shaft, and failure of which would severely jeopardize the lateral stability of the entire structure. Also thin sections of shaft type staging do not have an appreciable level of ductility which can be taken advantage of in dissipating seismic energy and con-

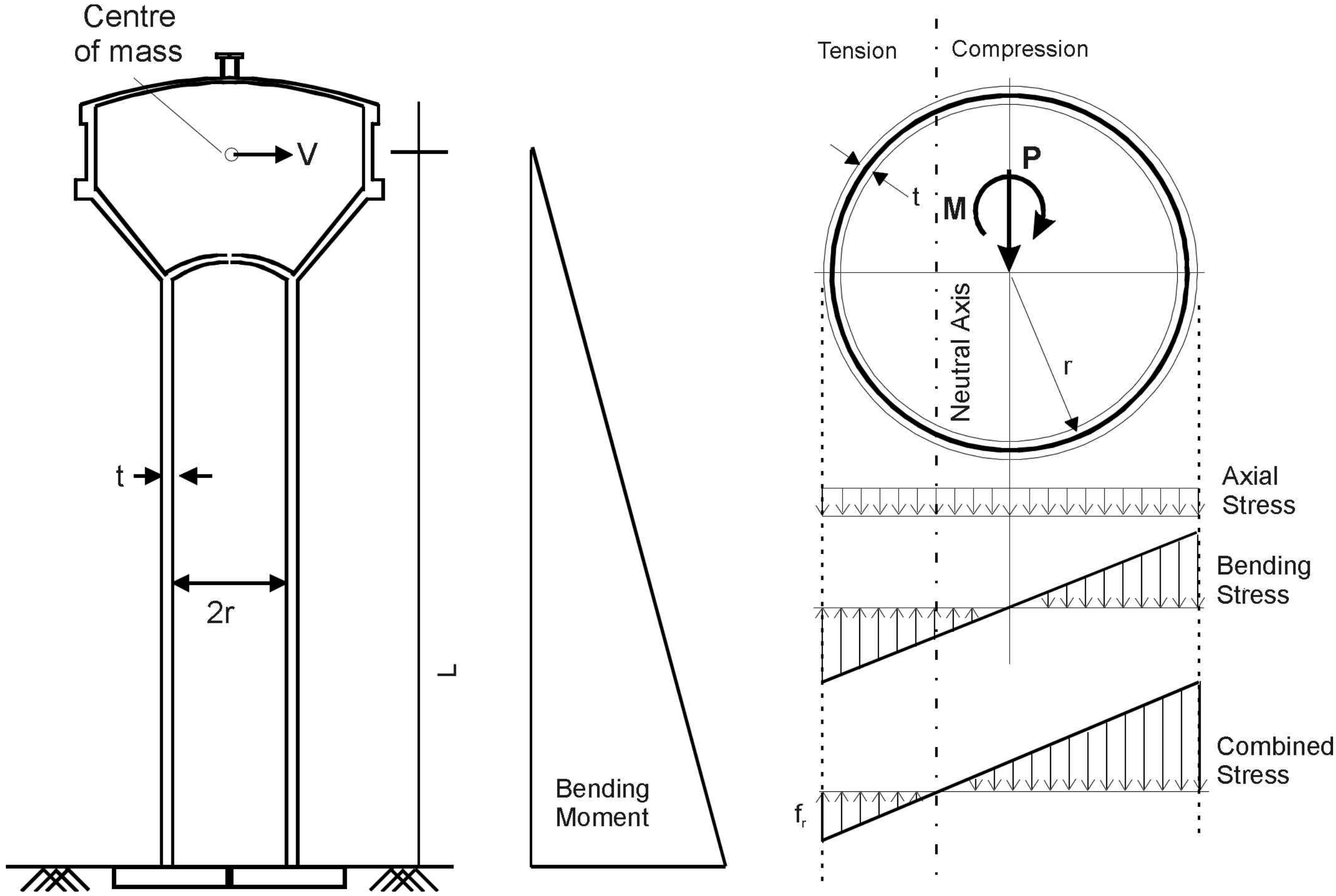

Figure 7. Stresses developed in shell staging.

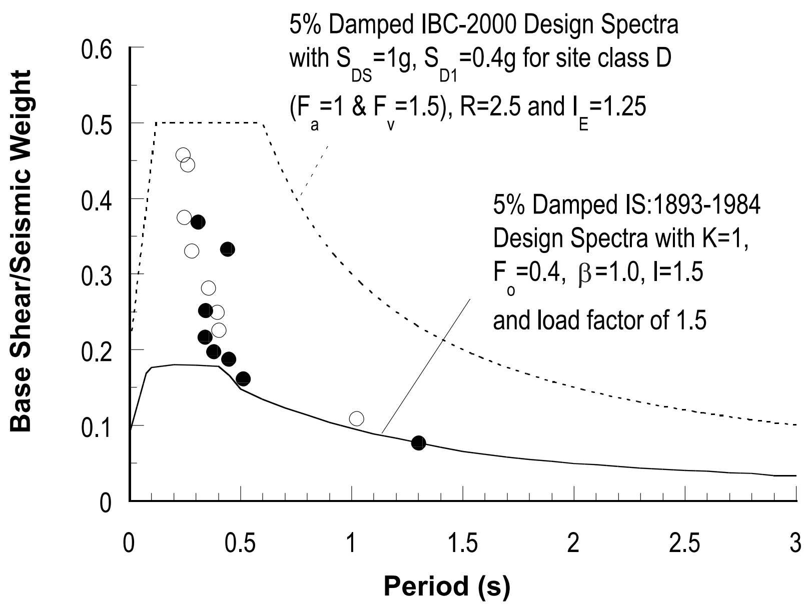

Figure 8. Comparison of available shear strength against tensile cracking of eight tanks with base shear strengths required by IS:1893-1984 and IBC 2000 codes, respectively. Open circles represent tank-empty condition while full circles represent tank-full condition.

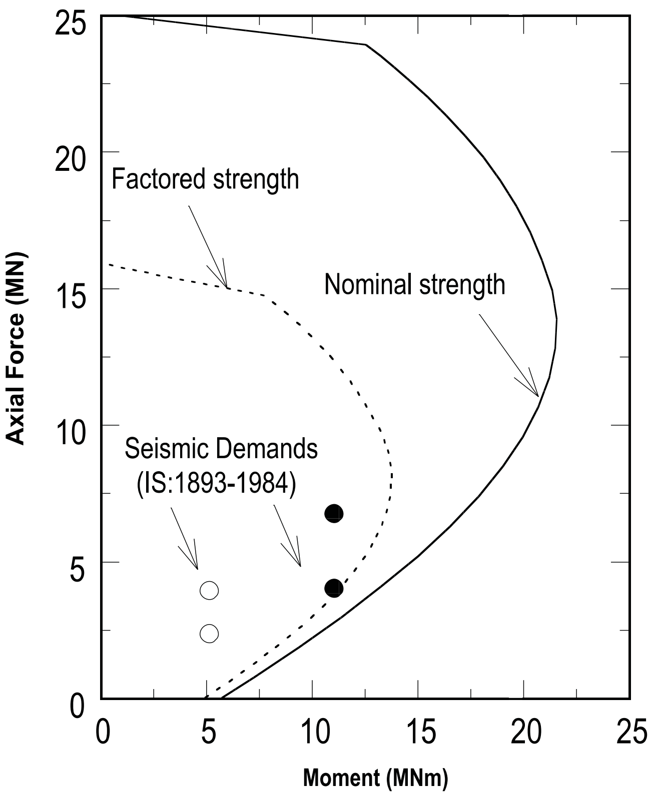

Figure 9. Envelope of factored and nominal strengths (interaction diagrams) for staging section near the base of the Chobari tank and demands expected for tank-empty and tank-full conditions.

sequently reducing design forces. For the above reasons, advanced codes such as IBC 2000 specify that such non-building structures be designed for seismic forces much larger than that which would be needed for a building system with similar dynamic properties. Currently, IS:1893-1984 underestimates the forces by at least a factor of 3 for water tanks.

The slender staging that results from the low design forces is a very unfavorable feature for seismic areas. Furthermore, there are no provisions in IS codes for ductile detailing of shaft type (thin shell) tank stagings though they are expected to undergo inelastic deformations during ultimate earthquake loads. It has been found that circular thin RC sections with high axial load behave in a brittle manner at the flexural strength and, therefore, should be avoided. In comparison, frame stagings of water tanks can be detailed according to provisions of IS:13920-1993 and IS:11682-1985 which refers to the ductility requirements of IS:4326-1976. The failures of framed staging in epicentral tract was primarily due to non-compliance of ductility provisions of IS codes intended for earthquake resistance, in addition to slender and weak frame members resulting from low seismic design forces.

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