The Behavior of Special Structures During the Bam Earthquake of 26 December 2003

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ABSTRACT: *On 26 December 2003 an earthquake of magnitude Ms = 6.5 with a focal depth of about 8km occurred in southeastern Iran. The earthquake caused intense ground shaking throughout the affected area. Special structures such as on-grade steel oil tanks, elevated tanks, and industrial equipment were damaged during the earthquake. This paper presents the results of an investigation of the behavior of these special structures in Bam. Strong motion characteristics as recorded by accelerograms are discussed, as well as the failure modes of structures and components located within the affected area. An investigation into the response of an electrical transformer was carried out as a case study of a simple system.*

Keywords: Bam earthquake; Special structures; Critical Facilities; Damage assessment; Water tank; Oil tank; Electrical substation

1. Introduction

In recent decades, seismic disasters have claimed a significant number of victims and caused physical damage and direct economic loss. Each earthquake also causes indirect loss and economic impact such as environmental pollution and work stoppages because of damage to special structures and equipment. The Bam earthquake in southeastern Iran on 26 December 2003 (*Ms* = 6.5) occurred at 05:26:26*am* local time. The epicenter of the earthquake was at 29.01*N*-58.26*E*, southwest of the city [1]. The focal mechanism of the earthquake was reported as strike slip and the focal depth was about 8*km* [2]. The Bam fault, in a nearly north-south direction, passes from the vicinity of Bam city (less than 1*km* east of Bam) between the cities of Bam and Baravat.

Special structures such as elevated water tanks and electrical facilities were damaged during the event and some industrial complexes were closed as a result of heavy structural and/or non-structural damage.

2. Strong Motion Characteristics

The ground motion time histories of the Bam event were recorded by 23 stations of the Iranian National Strong Motion Network [3]. The closest instrument to record the earthquake was located in Bam itself with a focal distance of about 12*km*. The corrected acceleration histories of both horizontal and vertical components of the main earthquake recorded at the aforementioned station are shown in Figure (1).

Based on the recorded data at Bam station, the peak ground acceleration of the horizontal component of the earthquake were 775cm/sec^2 for perpendicular and 623cm/sec^2 for parallel components to the fault direction. Peak ground acceleration of the vertical component was 992cm/sec^2 [1]. The damage distribution of structures in the earthquake affected region, and data recorded at Bam station, indicated the directivity effect of near-fault ground excitation [1].

3. Distribution of Special Structures

As shown in Figure (2), several essential facilities and industrial structures are located in the focal region and various types of industrial and special structures experienced the strong ground motion in the earthquake affected area. A significant number of industries are concentrated in the Bam Industrial Region, 1*km* south of the city. The structural system of the main industrial buildings in this region is

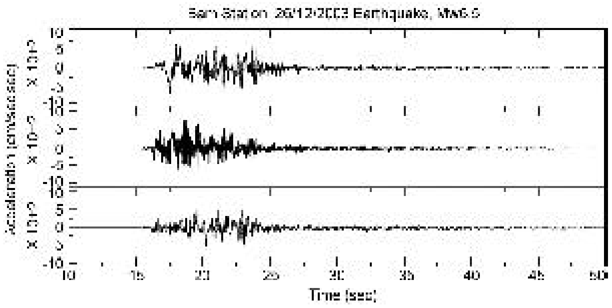


Figure 1. Corrected acceleration history of Bam Earthquake recorded at Bam station [1].

generally steel moment resisting gable frames or industrial frames with light-weight sloped truss systems.

There is a chemical plant belonging to the Roghan Jonoub Company next to the Bam Industrial Region that features six on-grades cylindrical and three elevated steel oil tanks. The 230/132kV electrical substation of Bam, one of the most important facilities in the stricken area, is located along a highway between Bam and Baravat, less than 5km from the faulting fissure.

4. The Response of Structures

4.1. Water Tanks

4.1.1. Elevated Tanks

A concrete elevated tank approximately 20m in height and 350m^3 in capacity was located at Bam Fire Station. The tank was designed and constructed about 32 years before the seismic event and earthquake induced loads were not taken into account during the design process. A tower with six rectangular columns supported the tank with the columns joined with rectangular beams at different elevations. Brick infill walls approximately 2.5m in height were constructed between tower columns to make an office beneath the tank, see Figure (3) .The tank was nearly empty at the time of the earthquake.

The response of RC elevated water tanks in past earthquakes shows that beam-to-column joints in these types of structure are susceptible to ground shaking [4]. Following the Bam earthquake, the *RC* tower of the aforementioned tank cracked, but did not collapse.

Inaccurate detailing was the major reason for the tank damage. As shown in Figure (4), the concrete column cracked near the beam-to-column connection and the longitudinal reinforcing bars buckled at that position. The main reason for this type of damage was the lack of transverse bars on the critical length of the column near the beam-to-column connection, which has a high potential for plastic hinge formation. Although, according to the Iranian concrete code (*ABA*) [5], the maximum allowable spacing between stirrups is 250mm, the spacing between transverse stirrups in the tower *RC* columns was much greater. Another failure mode of the tower was damage to beams adjacent to the column joint, in which the crack penetrated to the column, see Figure (5).

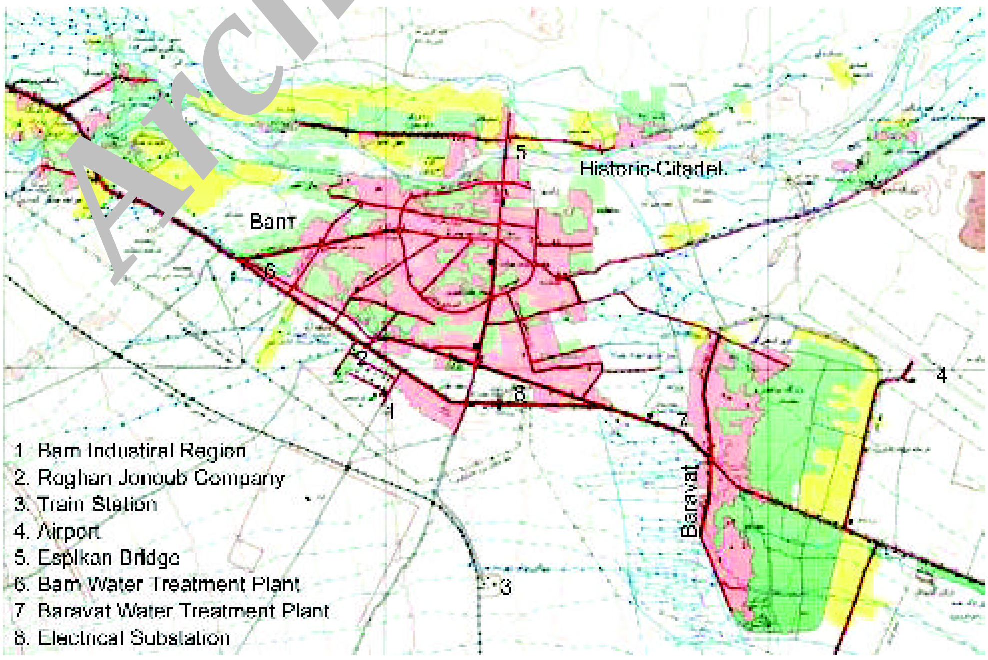
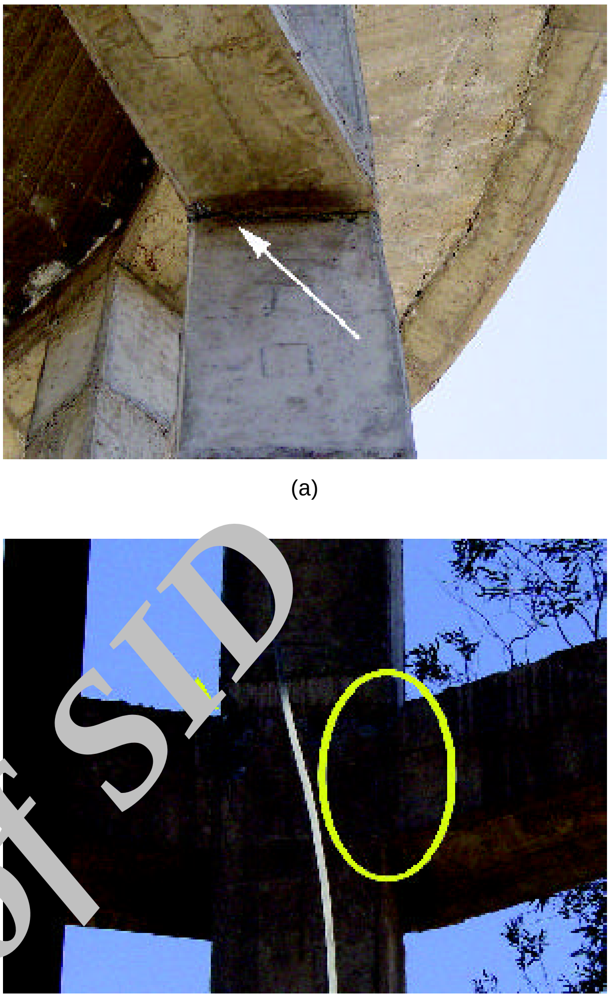


Figure 2. Locations of major urban and industrial facilities.

Figure 3. General view of the Bam elevated RC tank.

Figure 4. Inaccurately detailed cracked RC column [1].



(a)

(b)

Figure 5. Damage to beam next to column joint.

Several steel elevated water tanks experienced the strong ground motion, but most of them suffered no damage. Buckling of the slender bracing and rupture of poorly detailed bracing connection were common failure modes in damaged steel elevated tanks.

4.1.2. Underground Tanks

The Bam water treatment plant is located about 2*km* southwest of the city. There are three underground tanks at the site. The tanks had no visible structural damage. Soil settlement of about 10*cm* took place in the earth fill of each tank and tensile cracks were observed at the top of the earth fill, see Figure (6). None of the buildings in the plant suffered serious damage and the plant was operable after the earthquake.

The Baravat water treatment plant is constructed over the Bam fault. There were two underground water tanks at this plant. Both tanks are stone masonry. Before the seismic event, both tanks worked at full capacity, but the plant suffered major damage to tanks and annex structures during the earthquake and was forced to shut down. All of the annex buildings, including the chlorination building, collapsed completely, see Figure (7). These structures were un-reinforced brick masonry buildings. Leakage from the tank wall and bottom occurred after the earthquake and cracks were also found at construction joints on the masonry retaining walls surrounding the tank, see Figures (8) and (9).

(a)

(b)

Figure 6. Settlement and tensile cracks observed in tank earth fill.

Figure 7. Collapse of chlorination building.

Figure 8. Leakage of water from tank wall.

4.2. Bridges

In general, bridges sustained little or no damage. The most affected bridge, Espikan Bridge north of Bam near Arg-e Bam, sustained little damage. Espikan Bridge is a uniform bridge with an *RC* deck and stone masonry columns and 14 spans across the Poshtrood River, see Figure (10). As shown in Figure (11), the RC bent caps of the bridge cracked with the longitudinal movement of the deck in the north-south direction. No visible damage occurred to

Figure 9. Cracks observed at construction joints of surrounding wall

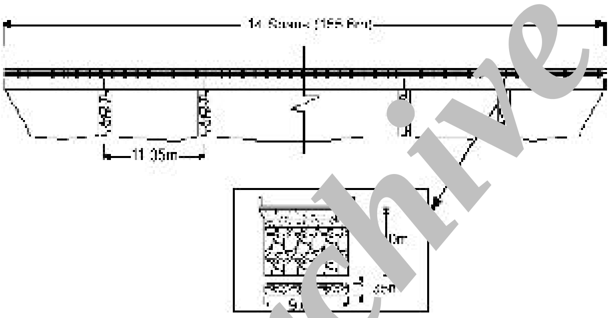


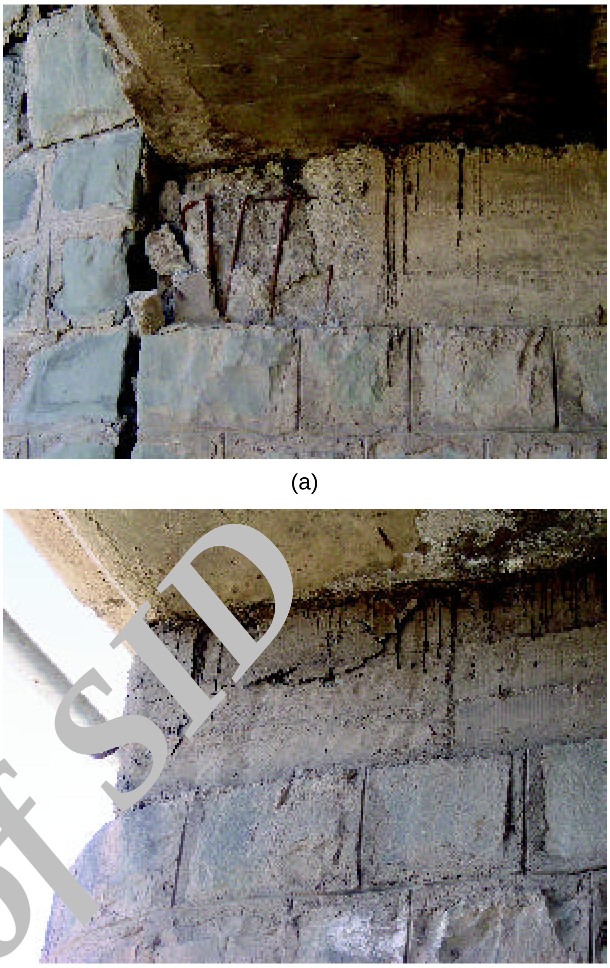
Figure 10. Espikan Bridge.

the deck slab as a result of the pounding of separate parts of the superstructure thanks to sufficient joint width and the bridge was in service after the earthquake.

The Darzin Bridge also experienced longitudinal movement of the superstructure and the stone abutment cracked as a result of settlement of the abutment, see Figure (12). However, the bridge was still safe for use after the earthquake. No structural damage occurred to other observed bridges in the affected region.

4.3. Industrial Frames

Steel gable frames are common in industrial structures in Iran. Several steel gable frames in Bam Industrial Region and some other industrial sites near the epicenter subjected to strong ground motion. No significant structural damage occurred in gable frames, but non-structural damage was observed. Light-weight roofs, good design and acceptable



(a)

(b)

Figure 11. Damage to RC bent caps from deck movement.

Figure 12. Settlement of Darzin bridge abutment.

supervision during construction are some reasons for the good behavior of these structures during Bam earthquake. Failure modes in these structures are described below.

4.3.1. Damage to Annex Buildings

As shown in Figure (13), failure of annex buildings was a typical damage mode for industrial structures with annex buildings. Annex buildings are generally brick masonry low-rise buildings constructed with adjacent gable frames without joints. Failure of annex buildings was, in most cases, caused by torsion due to asymmetric distribution of resistant walls or pounding of an adjacent industrial structure.

Figure 13. Damage to annex building of an industrial site [1].

4.3.2. Damage to Infill Walls

Failure of infill walls was the most common damage mode of industrial structures. The main reason for this mode of failure was lack of horizontal anchors and/or wall posts to restrain the infill walls to the structure. As indicated in Figure (14), inaccurate detailing of the anchor connections to the structure and lack of overlap length caused failure of infill walls.

4.4. Equipment

Equipment in industrial plants and critical urban sites such as power station suffered heavy damage. The major reason for this, especially in industrial sites located at Bam Industrial Region was the collapse of mechanical buildings. Mechanical buildings in most observed plants were un-reinforced brick masonry buildings with inaccurate detailing and weak materials that are seismically vulnerable. During the earthquake, the collapse of mechanical buildings caused heavy damage such as the rupture of connected pipes and residual deformation of equipment components, see Figure (15). Damage to equipment resulted in the closure of industrial plants after the main earthquake.

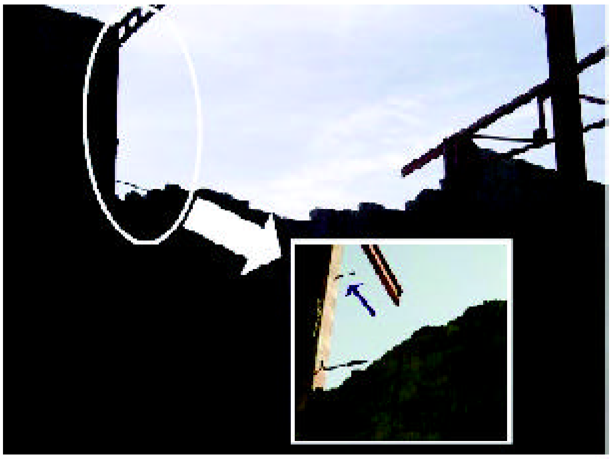


Figure 14. Failure of infill walls due to inaccurate detailing of anchors [1].

As mentioned before, the electrical substation was one of the critical facilities of the affected area. It is composed of two sections for $230kV$ and $132kV$. The equipment in this station sustained heavy damage. In general the extent of damage in the $230kV$ section was greater for the $132kV$ section. More than 13 bushings in the $132kV$ section cracked and collapsed, see Figure (16). Both $132kV$ and $230kV$ transformers moved due to the sliding response of equipment. One $230kV$ transformer moved about $40cm$ from its original position. The movement of transformers caused the base rails to sustain plastic deformation. Figure (17) indicates the sliding response of the $230kV$ transformer to ground shaking.

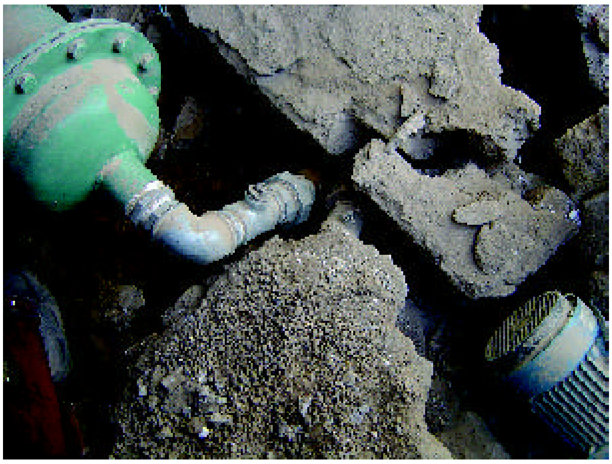
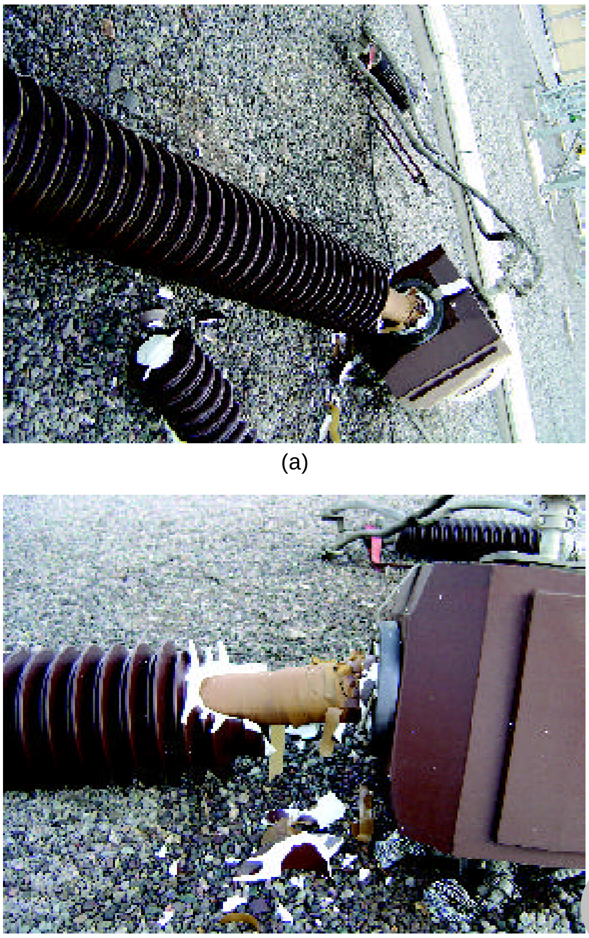


Figure 15. Damage to equipment in the collapse of mechanical buildings [1].



(a)

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Figure 16. Damage to bushings at Bam substation.

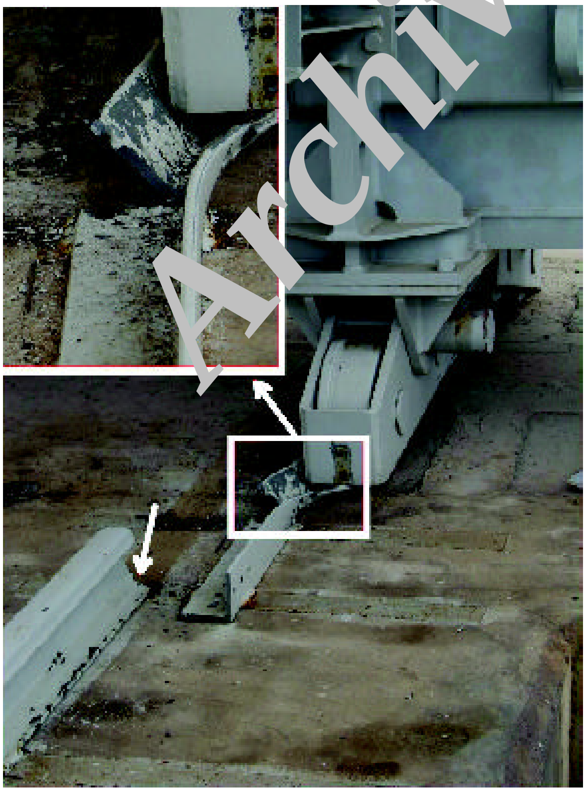


Figure 17. Displaced 230kV transformer [1].

4.5. Cylindrical Oil Tanks

Three out of six on-grade steel oil tanks at Roghan Jonub Company (see part 3) experienced leakage of liquid from roof-to-wall junctions from sloshing during the quake. Other damage modes such as elephant foot buckling, rupture of rigid piping, and tank were not observed in these tanks. Figure (18) shows the leakage of oil from on-grade tanks.

Figure 18. Leakage of oil from tank due to sloshing [1].

A cylindrical on-grade gasoline tank next to Bam electrical power station, which was nearly empty, suffered heavy damage. Rigid piping connected to the tank ruptured, probably from the inaccurate erection of the pipes, see Figure (19).The tank foundation was damaged due to tank uplift, but shell buckling did not occur, see Figure (20).

4.6. Elevated Oil Tanks

Elevated oil tanks at the Roghan Jonub plant were severely damaged and failed to contain the oil because of the failure of piping connections, see Figure (21). Also, as shown in Figure (22), a tank tower column punched the tank shell.

Figure 19. Rupture of pipe connections.

Figure 20. Damage to tank foundation due to tank uplift.

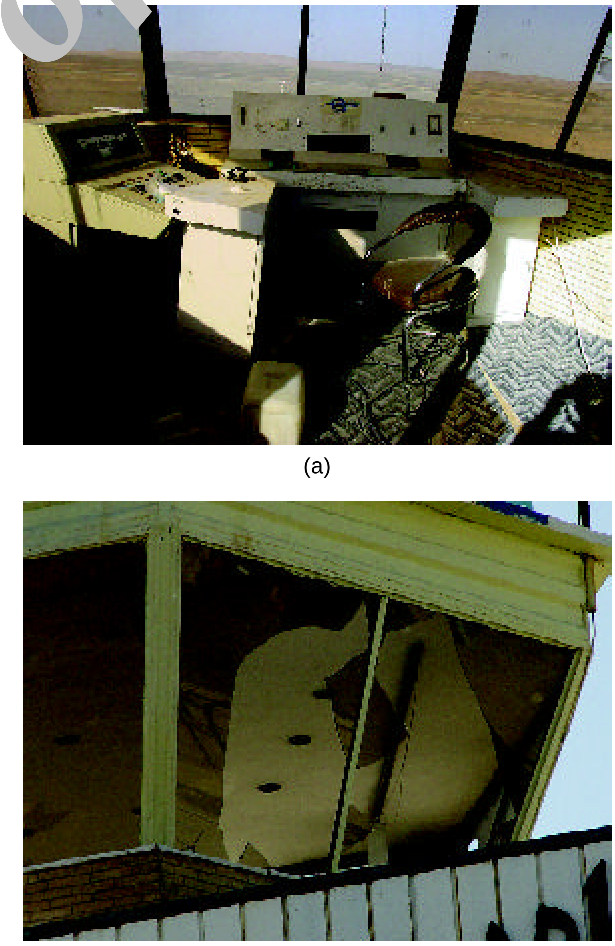
Figure 21. Leakage of oil due to rupture of pipes [1].

Figure 22. Punching of tank shell [1].

4.7. Critical Facilities

4.7.1. Airport

Bam Airport is located north of Bam between Baravat and Arg-e-Jadid. The control tower of the airport was closed because of heavy non-structural damage, see Figure (23). Since no structural member suffered serious damage, the airport brought back to full operation with the use of a portable control unit. Non-structural components also suffered heavy



(a)

(b)

Figure 23. Damage to airport control tower.

damage in the earthquake.

Most masonry infill walls at the airport cracked, Figure (24). Some false ceiling panels concealing power cables and such fell. No structural damage occurred due to the pounding of adjacent blocks, but finishing surfaces cracked or fell off at construction joints. The facade bricks of the terminal building fell off and damaged equipment and air conditioners, see Figure (25).

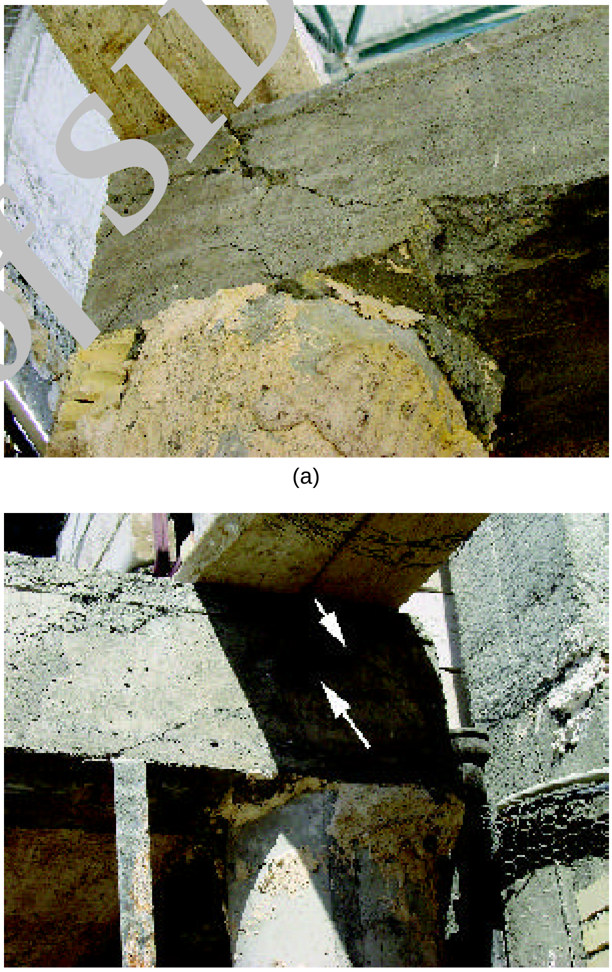
Figure 24. Damage to masonry infill walls at airport.

Figure 25. Damage to air conditioners.

4.7.2. Train Station

The Bam train station is under construction at a site south of Bam city. The structural system of the main terminal is a moment resisting *RC* frame with lightweight space trusses for the ceiling. Infill walls in the main building were cracked and facades were damaged from the strong ground motion, see Figure (26). Figure (27) shows shear cracks that occurred at some beam-to-column connections in the one-story *RC* frames.

Figure 26. Damage to façade at the Bam train station.



(a)

(b)

Figure 27. Shear cracks observed on beam-to-column joints at train station.

5. A Case Study of the Response of an Electrical Transformer

The response of a transformer to pulse-type near-fault base excitation was considered. The transformer is the rigid block shown in Figure (28), which can oscillate about the centers of rotation (o and o'). The block may

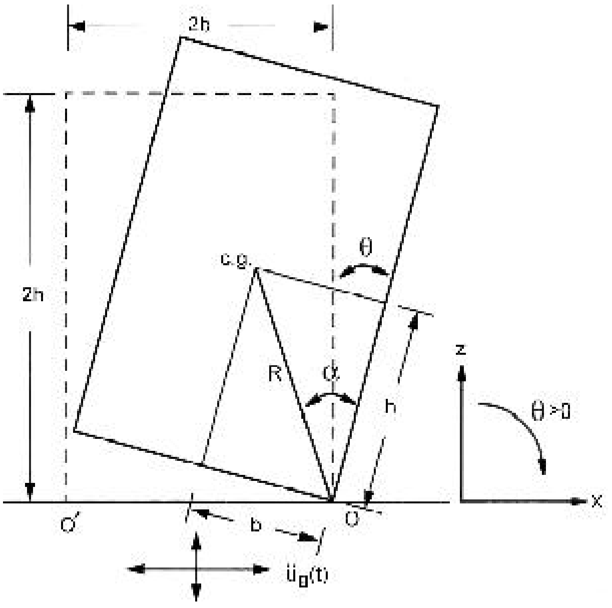


Figure 28. Schematic of a rigid block in rocking motion [6].

translate with the ground, slide or rocking, depending on the level and form of ground excitation [6].

Shenton [7] showed that, depending on the width-to-height ratio of the block, static friction coefficient and magnitude of base acceleration, there is a slide-rock mode of oscillation in addition to pure slide and pure rocking modes. Assuming that the coefficient of friction, μ, is greater than *tan* α (α = slenderness), the horizontal acceleration required to induce rocking should be at least $a_p = g\tan\alpha$. Assume that the rigid block in Figure (27) is about to enter rocking motion due to positive base acceleration, where $p^2 = 3g/4R$ and $R = (b^2+h^2)^{0.5}$ and p is almost equal to 2*rad/sec* for electrical transformers [6].

Makris and Roussos [6] proposed the following approximate expression to estimate the minimum acceleration which can make a rigid block overturn:

$$\frac{a_{po}}{\alpha g} \approx 1+\beta\frac{\omega_p}{p} \tag{1}$$

where $p^2 = 3g/4R$ and $R = (b^2+h^2)^{0.5}$; a_{po} is the minimum overturning acceleration of the pulse; α is the angle of slenderness; and p is almost equal to 2*rad/sec* for electrical transformers [6]. For one-sine pulse-type excitation, β is equal to 1/6.

In view of the relatively long duration of the coherent pulse, the range of interest of the frequency ratio, ω_p/p, for electrical equipment with p = 2*rad/sec* (such as electrical transformers), is $0<\omega_p/p<3$. Within this range of oscillation, the minimum overturning acceleration spectrum of cycloidal pulses is nearly linear. The ground motion acceleration history of the Bam event in the fault-normal direction, indicated in Figure (2), was modeled as a one-sine pulse type excitation and the acceleration, velocity and displacement history of such an excitation can be given as follows:

$$\ddot{u}_g(\tau) = \omega_p\frac{v_p}{2}\sin(\omega_p\tau), 0\le\tau\le T_p \tag{2}$$

$$\dot{u}_g(\tau) = \frac{v_p}{2}-\frac{v_p}{2}\cos(\omega_p\tau), 0\le\tau\le T_p \tag{3}$$

$$u_g(\tau) = \frac{v_p}{2}\tau-\frac{v_p}{2\omega_p}\sin(\omega_p\tau), 0\le\tau\le T_p \tag{4}$$

Consider the pulse duration of T_p = 1.3*sec* and *a* velocity amplitude of V_p = 1.6*m/sec*, which are approximations of the duration and the velocity amplitude of the first main pulse of the record. The equivalent pulse-type motion is indicated in Figure (29).

Using the approximate (Eq. (1)) and equivalent pulse (Eq. (2)) the ω_p/p ratio is approximately equal to 2.4, which is less than 3. Thus we obtain:

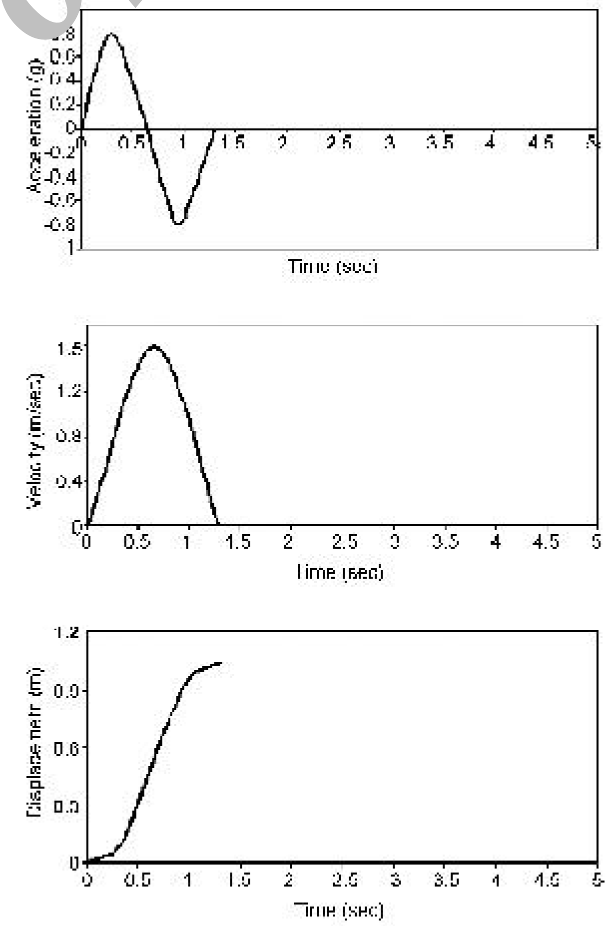


Figure 29. Fault-normal component of acceleration, velocity and displacement modeled as a pulse motion.

$$a_{po} = g\,(1+2.4\times1/6)=1.4g\alpha \qquad (5)$$

The plot of a_{po} for various slenderness ratios is shown in Figure (30).

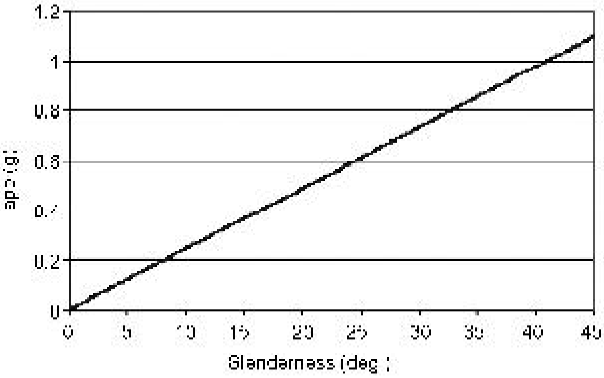


Figure 30. Plot of “apo” versus slenderness.

As indicated in Figure (29), the peak ground acceleration required for the overturning of a transformer of α = 25° is 0.61g, which is less than the *PGA* of the Bam earthquake in the fault-normal direction. It seems that the existence of base rails and connections to the transformers was the main reason for the stability of the transformers in the Bam station.

6. Conclusion

The seismic event of December 26, 2003 in south-eastern Iran imposed heavy damage to special structures and critical facilities in the earthquake affected area. Inaccurate detailing and use of weak materials were reasons for damage to many industrial structures.

Complete or partial collapse of mechanical buildings caused serious damage to equipment.

The *RC* tower of the elevated water tank cracked, but steel elevated water tanks suffered no serious damage. There was no visible structural damage to the Bam *RC* underground water tank, but the underground masonry tanks at Baravat water treatment plant cracked. Inadequate erection of oil tank rigid piping caused the rupture of piping connections and subsequent leakage of liquid.

No visible structural damage occurred to industrial gable frames, but nonstructural components of these structures were severely damaged. Although bridges sustained little or no damage, longitudinal movement of the superstructure was a common damage mode in bridges.

In conclusion, damage to industrial and critical facilities caused a heavy direct and indirect economical and social impact.

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