Performance of Batten Columns in Steel Buildings During the Bam Earthquake of 26 December 2003

B. Hosseini Hashemi and M. Jafari S.

Structural Engineering Research Center, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran, email: behrokh@iiees.ac.ir

ABSTRACT: *In recent decades, the seismic behavior of steel and steel reinforced concrete buildings has been, in many cases, unsatisfactory. In fact, after the 1989 Loma Prieta, 1994 Northridge and the 1995 Kobe earthquakes, several engineered steel structures suffered heavy damage or collapsed due to failures in their structural components or welded parts. In some countries, non-engineered buildings using reinforced concrete or steel columns and beams (particularly shopping centers and schools) were responsible for the majority of casualties because of lack of safety procedures against the effects of horizontal seismic forces. In Bam, many residential, commercial and governmental buildings were steel structures. Use of built up columns with batten plates is very common in different regions of Iran. The design of the batten columns is guided by the INBC, which is limited to the calculation of the axial capacity of these column under gravity loads. In order that the shear deformations do not reduce the axial capacity of the batten columns, some recommendations are also provided by the INBC. Taking to account the INBC recommendations the column is expected to buckle along the axis parallel to batten plates in which the buckling load is not influenced by the shear deformation. In this paper, the behavior and failure modes of steel buildings during the Bam earthquake are briefly presented. The different failure modes of batten columns observed in damaged buildings are discussed and compared with those that are expected to happen when a batten column is designed according to code provisions. An initial evaluation of damage patterns from the Bam earthquake revealed failure modes in columns, such as global buckling about the axis perpendicular to batten plates (hollow axis), local buckling, batten plate failure, and lateral torsional buckling. This demonstrates that the seismic performance of batten columns is unsafe and their use must be avoided in regions characterized by high seismic risk, at least until their behavior under dynamic loads is better understood. Finally, it is necessary to update the INBC, introducing specific seismic requirements taking into account the importance of inelastic structural response to large earthquakes and criteria based on "performance-based design" and "capacity design" principles.*

Keywords: Bam earthquake; Steel building; Batten column; Batten plate; Shear softening; Khorjini connection

1. Introduction

After the 1989 Loma Prieta, 1994 Northridge and the 1995 Kobe earthquakes, several engineered steel structures were subjected to heavy damage or collapse, due to failures in their structural components or in welded parts [1-8]. In other countries, non-engineered buildings using reinforced concrete or steel columns and beams (particularly shopping centers and schools) were responsible for the majority of casualties because of lack of safety procedures against the effects of horizontal seismic forces [9].

The unsatisfactory seismic behavior of steel buildings was also observed during the Bam earthquake in Iran. Many residential, commercial and governmental steel buildings there have been constructed in a fashion similar to those existing in other regions of Iran, using built-up columns with batten plates and khorjini connections. The latter consists of a pair of continuous beams spanning several columns and connected to the column sides by means of angle sections. Different structural systems used in these buildings are: khorjini frames in two braced directions; khorjini frames braced in the direction of the khorjini connection; khorjini frames braced perpendicular to the direction of the khorjini connection; unbraced khorjini frames; simple braced frames in one direction; simple braced frames in two directions; and simple unbraced frames.

The most common type of column in steel buildings in Iran is built-up members connected by means of batten plates. The main reason for the use of this type of column is the absence of wide-flange column sections in Iran. Special provisions for designing batten columns are presented in the Iranian National Building Code (INBC), part 10 [10]. The code provisions are limited to the calculation of the axial capacity of these columns under gravity loads.

There are also provisions for prevention of local failure of column elements and a strong recommendation that the exertion of bending moment about the hollow axis be avoided. By applying these provisions to the design of batten columns under axial load, it is expected that undesirable failure modes will be prevented and the overall buckling of the column about the axis parallel to the batten plates will be the only dominant failure mode of the column. Also, when the column is under both axial load and bending moment about the axis parallel to the batten plates, the axis of buckling and bending coincide. Adversely, when the column axis bending is about the hollow axis, lateral torsional buckling occurs because the column's weak axis is perpendicular to its bending axis.

As a result of the earthquake, many steel structures sustained major damage and different modes of failure were observed in their structural elements. In most of these buildings, batten columns with different structural systems were used. Failure studies of batten columns in Bam show the different local failure modes and also global buckling about hollow axis. These different failure modes reveal uncertainties about the seismic behavior of these columns.

Many studies on the behavior of batten columns have been done by different researchers. Most of these studies focused on the buckling of these columns under gravity loads. Unfortunately, there are no studies on the behavior of batten columns under earthquake excitation [11]. Despite the prevalence of batten columns in low seismicity regions, including European countries such as Germany, there are no seismic provisions for the design of these columns in building codes.

In order to better understanding the behavior of batten columns under dynamic loads, research and testing programs are urgently needed in Iran [12]. The results of such programs can be used to update the *INBC*, and introduce specific seismic requirements that recognize the importance of inelastic structural response to large earthquakes and criteria based on performance-based design and capacity design principles.

Many of buildings in Bam were damaged during the devastating earthquake. In most of steel buildings, batten columns with different structural systems such as simple frames, simple braced frames and frames with “khorjini” connections, were used. Failure studies of batten columns in Bam show the different local failure modes and also the global buckling about hollow axis. These different failure modes show the existence of uncertainties in seismic behavior of these columns.

In this paper, different failure modes of steel buildings and batten columns, observed in Bam after the earthquake, are presented. In constructing steel structures in most regions of Iran the batten columns are used. Therefore, in order to understand the seismic behavior of these types of columns, more researches in seismic design or rehabilitation of existing buildings with these columns, are needed.

2. The Performance of Steel Buildings

Different failure modes in steel buildings, including overall collapse and damage to or failure of structural components such as columns, braces and connections, were observed in Bam after the earthquake. The most common type of column used was the batten column. In some buildings, box columns were used and, with this type of column, failure modes such as rupture in the longitudinal joint, see Figure (1) and local buckling, see Figure (2) were observed.

The concentrically X braced system using channels, angles, I sections and bars is the most

Figure 1. Rupture of longitudinal joint in box column.

Figure 2. Local buckling of box column.

common type of bracing in steel braced frames in Bam. The observed failure modes in these braces were out of plane buckling and rupture of connections. The major reasons for these failures were construction defects and incomplete welding of connections. Some examples of bracing failures are shown in Figures (3) and (4).

Beam to column connections in most steel buildings in Bam are khorjini and simple connections with top and bottom angles. Weld fractures, rupture of connection devices and rupture of connection plates from batten columns were failure modes observed in these connections. Some examples of these failures are shown in Figures (5) to (7). Because of the wide range of failures in connections, one can concluded that the collapse of structures was mostly initiated by connection failures. Failure modes in steel structures such as were seen in Bam have been reported in most earthquakes [1-8].

Figure 3. Rupture of connections in concentrically X bracing.

Figure 4. Out of plane buckling of concentrically X bracing.

3. Design Basis of Batten Columns

As previously mentioned, special provisions for the design of batten columns under axial load are presented in part 10 of the *INBC*. The most important difference between batten columns and columns with a continued web is the influence of shear flexibility on the axial capacity of batten columns when the column buckles about its hollow axis. To consider the effect of shear deformation on the axial capacity of batten columns buckled about its hollow axis, the equilibrium differential equation of buckled column is rewritten by considering the shear curvature in addition to bending curvature. Solving the equation introduces a coefficient to modify the column slenderness ratio for buckling about the hollow axis. This approach is commonly used in building codes, the only difference being the magnitude of the coefficient.

Figure 5. Weld rupture of web and top angle of connection and separation of column plate.

Figure 6. Rupture of seat angle of simple connection.

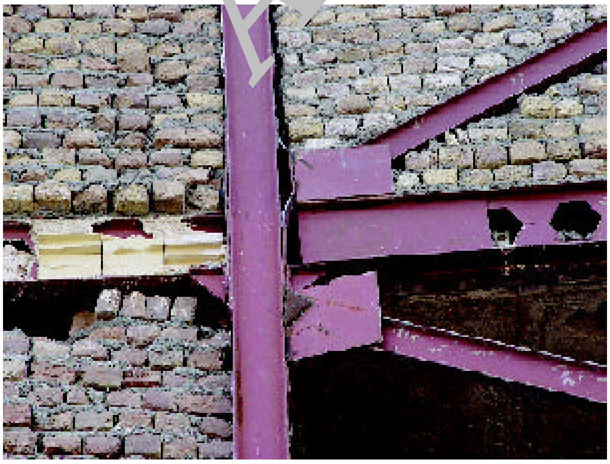

Figure 7. Separation of connection plate of batten column.

In part 10 of the *INBC*, an equation for the calculation of the modified slenderness ratio of batten columns that buckle about their hollow axis is introduced. Also, special provisions for details of batten plates, including their dimensions and distances from each others are presented. Meeting these provisions allows one to use the presented equation for calculation of a modified slenderness ratio. To ensure that the dominant failure mode of the batten columns is the overall buckling about the axis perpendicular to the hollow axis, it is recommended that the effective slenderness ratio of the column about the hollow axis be less than for the other axis.

Batten plates are the most important parts of batten columns and shear forces between chords induced by bending of the column are transferred by these components. In other words, the perfect operation of batten plates allows the batten column to have a similar performance to columns with unit sections.

If the column axial force is equal to P and the column lateral displacement at any arbitrary section due to the effect of axial force in the initial geometric imperfection is W, the bending moment M and the shear force V at this section will be equal to:

$$M = Pw \tag{1}$$

$$V = \frac{dM}{dx} = P\frac{dw}{dx} \tag{2}$$

With the assumption that the slope of the buckled column shape, dw/dx, is approximately equal to 0.02, the additional shear force due to the axial force becomes 2% of the magnitude of axial force. This shear force is only due to the inevitable initial imperfection of the column. According to the *INBC*, part 10, the shear force that is used in designing batten plates is equal to the first order shear force of the column due to column lateral loading or column end moments, plus 2% of column axial force. It is clear from the above discussion that the proposed design force of batten plates is mainly obtained when the column is under pure axial force. If the bending moment about the hollow axis applied to the column or the slope of the buckled column (*dw/dx*) is larger than 0.02, the magnitude of the applied shear force on the batten plates will become larger than that considered in the design code, and this may lead to premature failure of the batten plates. Therefore, it is strongly recommended that the induction of the bending moment about the hollow axis be avoided. Furthermore, the bending moment about the hollow axis can increase the axial force of chords and initiate premature local buckling of these members.

4. Overall Buckling of Batten Columns

The overall buckling of batten columns was observed in some steel buildings in Bam. An example of overall buckling in the columns of a pharmacy is shown in Figure (8). It is significant that the buckling has occurred about the hollow axis. As mentioned earlier, according to the code, this type of buckling is undesirable. The other important point revealed in Figure (8) is the occurrence of buckling in the top story of the building, in which columns have low gravity loads. This may be due to the increased column axial force through the effect of the high vertical component of the earthquake. Reyas-Salazar et al [13] studied the effect of vertical acceleration on the seismic response of steel frames with flexible connections. Another example of overall buckling of the batten column about the hollow is shown in Figure (9).

Figure 8. Overall buckling of batten columns about hollow axis In a pharmacy.

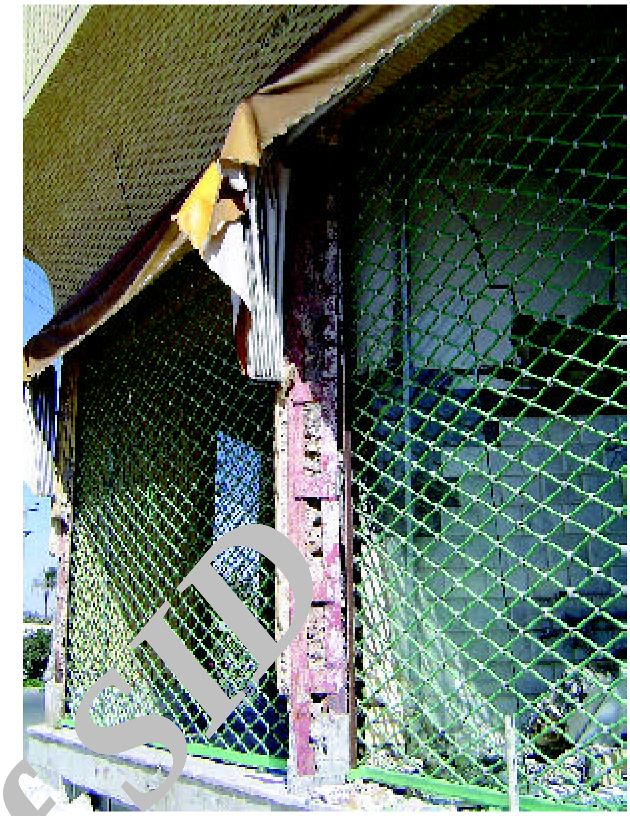

Figure 9. Overall buckling of batten columns about hollow axis in a store.

5. Local Buckling of Batten Columns

An example of local buckling in one of the chords of a batten column is shown in Figure (10). Because of the relative direction of batten columns and khorjini connections, in spite of code recommendations, a bending moment about the hollow axis could be applied to batten columns. This bending moment, as mentioned before, may lead to the occurrence of local buckling in batten columns, as shown in Figure (10).

Figure 10. Local buckling of one chord of batten column.

6. Lateral-Torsional Buckling of Batten Columns

Lateral-torsional buckling is a probable mode of failure in batten columns. Nevertheless, there is no special provision regarding lateral-torsional buckling of batten columns in the part 10 of the *INBC*. In some cases, lateral-torsional buckling was observed in batten columns in Bam. An example of this mode of failure is shown in Figure (11).

Figure 11. Lateral-torsional buckling of batten column in a store building.

7. Failures of Battens in Batten Columns

As previously mentioned, battens are the most important component of batten columns. In fact, shear transfer between the chords of a column is done through the battens. Therefore, failure of battens leads to separation of chords and a severe decrease in the axial capacity of a batten column.

Upon the failure of a batten plate, the distance between its adjacent battens is increased. The applied bending moment on adjacent battens also increases and could lead to failure of these and their adjacent battens. With an increase of distance between the battens, the magnitude of the modified slenderness ratio of the column about a hollow axis also increases and, hence, the axial capacity of the column may decrease or change the direction of buckling.

Special provisions for the design and detailing of battens in part 10 of the *INBC* is discussed in Section 3. Nevertheless, many cases of batten failure in batten columns were observed in Bam.

7.1. Rupture of Battens

Some examples of rupture in battens are shown in Figures (12) to (14). In Figure (12), the dimension of battens are smaller than those that are common in steel buildings. The rupture of these battens could occur due to incorrect design and construction, or usage of improper materials.

In Figures (13) and (14), battens having proper dimensions are observed. The rupture of these battens may be due to the increase of applied forces on battens relative to design forces in the codes. As mentioned, an increase of applied forces may result in the application of bending moment about the hollow axis or the occurrence of large deformations in columns. Such failures in battens are undesirable and must be prevented. It is evident that further study into the design forces of battens is required.

7.2. Ruptures of Batten's Welds

In many cases, the failure of battens in batten columns occurs in the weld of the battens to chords. Some examples of weld ruptures are shown in Figures (15) to (17). Because of the absence of quality

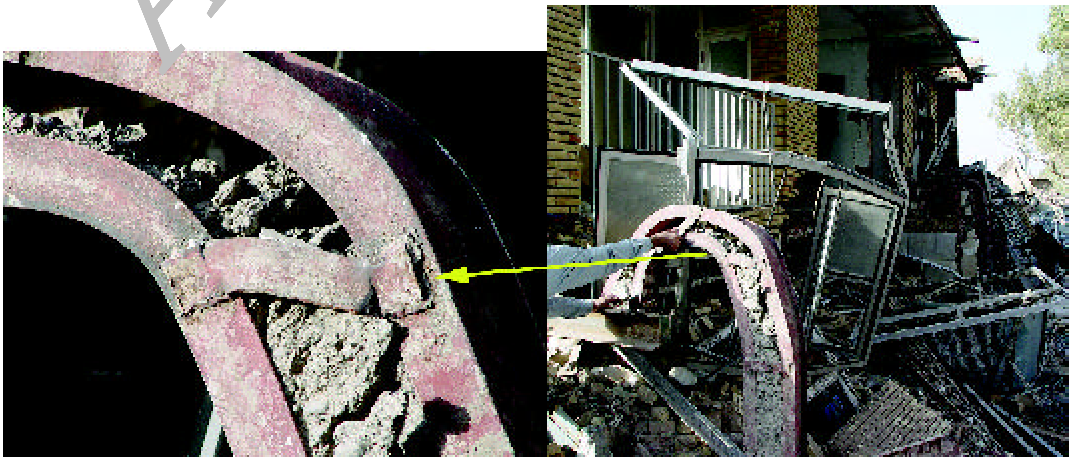

Figure 12. Rupture of battens in a two story residential building.

Figure13. Rupture of battens in a pharmacy.

Figure 14. Rupture of battens in a shopping center.

control for welding in Iran, the occurrence of weld failures in different components of steel buildings during earthquakes is expected. However, batten rupture may also lead to the rupture of batten welds. In the column shown in Figure (16), all of the battens failed at the welds. This failure may have led to separation of the chords and the collapse of the batten column.

Figure15. Weld rupture in battens of batten column in a pharmacy.

Figure 16. Weld rupture in all battens of batten column in a pharmacy.

Figure17. Weld rupture in battens of batten column in an insurance building

7.3. Plastic Shear Deformation of Battens

Plastic shear deformation of battens in batten columns increases the influence of shear in the capacity of batten column and also leads to a decrease in the distance between the chords, which may cause a decrease in the axial capacity of the batten column. An example of plastic shear deformation of battens is shown in Figure (18).

8. Splice Failure in Columns

In all types of steel columns, splices are important and their failure eventuate the collapse of columns and the structure. Design and detailing and construction of splices in columns must be scrupulous. An example of splice failure of a batten column is shown in Figure (19).

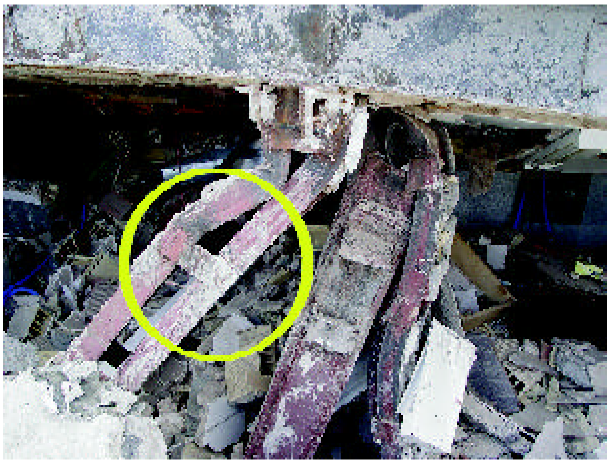

Figure18. Plastic shear deformation of batten of battens.

Figure19. Failure of batten column at splice location in kimia building.

9. Conclusions

A brief review the behavior and modes of failure of batten columns that have been observed after the Bam earthquake was presented. Important modes of failure of batten columns are overall buckling, local buckling of one chord, lateral-torsional buckling and batten failure. Some of these modes of led to a severe decrement in the axial capacity of the batten column and hence, and must be prevented.

More research is required on the seismic behavior of batten columns, which is clearly poorly understood at present. Such research is needed not only for the design of batten columns under earthquake excitation, but also for seismic rehabilitation of existing steel buildings constructed with batten columns and which are common throughout Iran. Because the existing provisions of codes for batten columns are based on static behavior under axial loading, it is proposed that the use of these columns in high seismicity regions be prohibited until codification of special seismic provisions for batten columns can be developed.

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