

ARASTIRMA MAKALESİ /RESEARCH ARTICLE

EFFECT OF SEISMIC LOADING TO PREFABRICATED CONNECTIONS

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ABSTRACT

Most of industrial buildings are prefabricated structures and built on high seismic risk zones. Prefabricated buildings must be earthquake resistant which can be possible if structural elements and their connections are properly built. In recent years, prefabricated buildings which have no RC walls were damaged heavily during earthquakes. In this paper, prefabricated industrial structures, damaged during Ceyhan (1998), Kocaeli (1999) and Düzce (1999) earthquakes, and reasons of structural damages are studied. Additionally design and construction precautions are given for building an earthquake resistant prefabricated structure.

Keywords: Prefabricated building, Earthquake, RC wall, Industrial buildings.

PREFABRİK BİRLEŞİMLERDE SİSMİK YÜKÜN ETKİSİ

ÖZ

Endüstriyel yapıların çoğu prefabrik yapılardır ve yüksek sismik risk altında olan bölgeler üzerine inşa edilmişlerdir. Bu yüzden prefabrik yapılar depreme dayanıklı olmak zorundadır ve bu ancak yapı elemanlarının ve bunların montaj detaylarının uygun olması ile mümkündür. Son 10 yılda, betonarme perdesi olmayan prefabrik yapılar depremlerde ağır hasarlar görmüşlerdir. Bu çalışmada; Ceyhan (1998), Kocaeli (1999) ve Düzce (1999) depremlerinde hasar görmüş prefabrik endüstriyel yapılar ve oluşan yapısal hasarların sebepleri araştırılmıştır. Ayrıca depreme dayanıklı bir prefabrik yapı inşa etmek için alınması gereken önlemler projelendirme ve imalat aşamaları için verilmiştir.

Anahtar Kelimeler: Prefabrik yapı, Deprem yükü, Betonarme perde, Endüstriyel yapı.

1. INTRODUCTION

In Turkey, due to 130 damaging earthquakes in the last 98 years (1900–2005) about 67000 people have died (700 per year), 200000 were injured, and 600000 structures were destroyed or heavily damaged. According to the seismicity map of Turkey (Fig. 1), 92% of the Turkish land, 95% of the population, and 98% of the industry lies on the seismically active ground (in Seismic zones 1 to 4).

Structural damage and collapse of precast buildings were widely reported throughout the epicentral regions of August 1999 Kocaeli and November 1999, Duzce earthquake in Turkey (Atakoy H, EERI 2000). Three types of structural damage were frequently observed in the one-story industrial buildings. Flexural hinges at the base of the columns; axial movement of the roof girders which led to pounding against the supporting columns or unseating of the roof girders; and out-of-plane

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movement of the roof girders which led to tilting of the beams and rotation off the supports.

In Turkey, history of prefabricated structure started in 1960. Prefabrication became more common during 1980s. Although earthquake and prefabricated structure behaviour were studied deeply and codes were prepared in other countries, no observations were made about this subject before 1960 in Turkey (PCI Handbook 1988, TS9967 1992). Prefabricated structure behaviour was studied after four important earthquakes. Those are;

- 1992 - Erzincan (Mw=6.8) 1998 - Ceyhan (Mw=6.3)
- 1999 - Kocaeli (Mw=7.4) 1999 - Düzce (Mw=7.2)

Erzincan earthquake (1992) was the most destructive of all. Statistical data of those earthquakes are given below (Table 1).

The earthquake in Ceyhan resulted in 145 deaths, more than 1500 injuries and damage to about 30,000 buildings. Out of these 30000 buildings, about 1000 collapsed including the collapse of 12 major reinforced concrete (RC) buildings in the town of Ceyhan (population: 100000), another 9000 experienced heavy to moderate damage and became uninhabitable while 20000 experienced light damage (Wenk, Lacave and Peter 1998). August 17th, 1999 Kocaeli and November 12th, 1999 Düzce earthquakes are the largest natural disasters of the 20th century in Turkey after the 1939 Erzincan earthquake. The official death toll is 39035 in the Erzincan earthquake. The official death toll is 17322 in the Kocaeli earthquake and 950 in the Düzce earthquake. During these two earthquakes, Gölcük, Değirmendere, Derince, Adapazarı, Gölyaka, Düzce and Kaynaşlı cities were almost completely destroyed. A total of 330000 residences were damaged, where the shares of light, moderate and severely damaged or collapsed units are 118000, 112000 and 100000, respectively (Sucuoglu 1999).

Total economic losses are estimated to be 10 billion USD, leading to a 6% shrinkage of the Turkish economy in 1999. The impact of 1999 earthquakes in Turkey are evaluated with an engineering perspective in this paper, and the causes leading to the observed damage are discussed. It can be said that the number of damaged prefabricated structures is less than the number of other damaged structure types.

Structural damage of industrial buildings caused damage of machines, hardware and materials. Main objective is to prevent industrial buildings from earthquake damage. Machines in some of the buildings 100 times more expensive and important than the building that they are placed. Prefabricated structure damages are generally observed in Adapazarı district.

2. INDUSTRIAL BUILDING AND RESIDENCE PREFABRICATION

Industrial buildings are tall and have big span lengths compared to residences. They can not be constructed as cast-in-situ structures, because of their beams which have big span lengths (10-25 m). In Turkey, 80% of industrial buildings are prefabricated structures and 90% of them are in Marmara, Ege and Akdeniz regions which are under high seismic risk. Prefabricated structures have rectangular columns with corbels. Beams are in trapezoidal shape or constructed as lambda system for roof slope (Fig.2). Assembly order is given below;

- Connecting columns to cast-in-situ foundation
- Connecting beams to columns
- Connecting purlins to beams
- Covering the roof

Prefabricated structural frames are formed by connecting columns to cast-in-place foundations and connecting beams with columns. Roof covering is made above purlins. Column–foundation connections are rigid while column–beam connections are constructed as rigid or moment released (Fig 3). If the subject is earthquake resistance, most important parts of prefabricated structures are joints.

Prefabricated residences are multi-story and have short span lengths (Fig 4). 0.05% of RC residence buildings are prefabricated residences. During last 20 years, number of damaged prefabricated residences is less than number of damaged prefabricated industrial buildings.

3. ASSEMBLY OF PREFABRICATED INDUSTRIAL STRUCTURES

Assembly order is very important for earthquake resistance of prefabricated structures. During 1998 Ceyhan, 1999 Kocaeli and 1999 Düzce earthquakes prefabricated structures were heavily damaged during construction. (Fig. 5) If no rigid column-beam and beam-beam connections are formed for resisting lateral

earthquake loads, RC walls must be constructed before assembling beams for preventing possible

earthquake damage during construction. In Adapazari, a prefabricated building, that have an area of 10000 m² is collapsed. This number is 45% of total damaged building area during 1999

Kocaeli and Duzce earthquakes. During 1998

Ceyhan earthquake, a 2800 m² building is heavily damaged at assembly stage (Fig. 5) This structural system had 20 m.long spans and 7.50 m tall frames.

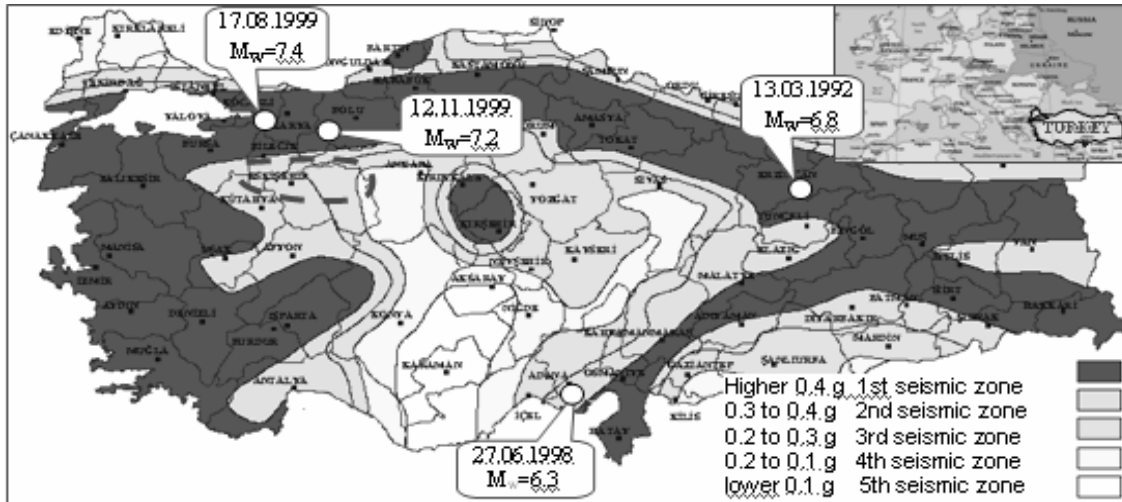


Figure 1. Earthquake zone map of Turkey

Table 1. Prefabricated structure damage of 17th August and 12th November 1999 earthquakes (Dogan 2000)

Location	Total	Heavily damaged	Mid-range damaged	Non-damaged	Damage Ratio (%)
İstanbul-Avcılar	54	-	-	54	0
İzmit	241	1	5	235	2.50
İzmit-Gölcük	35	-	-	35	0
Yalova	50	-	1	49	2.0
Adapazarı	98	16	8	74	24.50
Bolu	2	-	-	2	0
Düzce	1	-	-	1	0
Sum	481	17	14	450	



Figure 2. Photograph of Typical Single-Story Warehouse Facilities

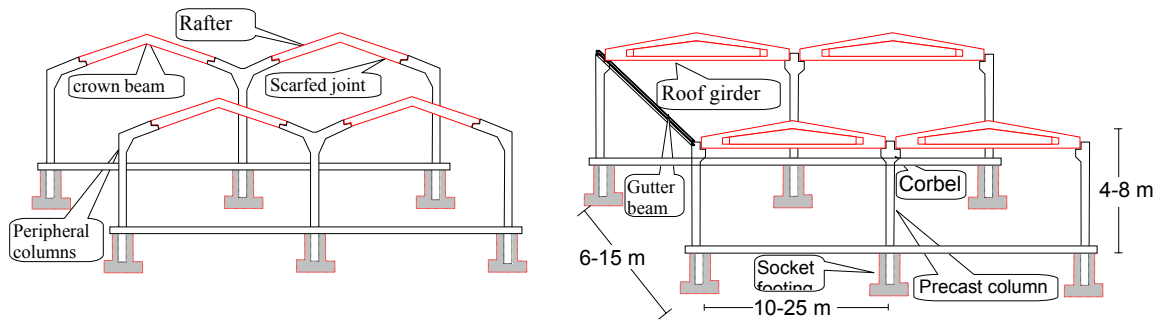


Figure 3. Prefabricated frame types (a) Transverse Elevation (b) lambda system



Figure 4. Photographs of multi-story precast building Facilities



Figure 5. Prefabricated Structure damage a-Ceyhan b-Kocaeli earthquake

Most common damage types are slipping of beams from corbels, failure of weak and short reinforcement bars of corbels and failure of connections because of using low strength grouts which are given in Fig 6 (Bayülke 1998). Adherence of precast and cast-in-situ concrete is not very good as known, so the same strength both from precast and cast-in-situ concrete can not be expected.

Bolts can be used for preventing adherence problems between steel bars and concrete (Fig. 7)

4. EFFECTS OF REINFORCEMENT AND CONCRETE QUALITY ON LATERAL DISPLACEMENT

Prefabricated structural elements are brittle because of their high concrete quality. In order to make these elements ductile, confinement distances must be reduced. Because of vertical and horizontal loads on starts and ends of columns, they make big lateral displacements. These lateral displacements can be reduced by RC cast-in-situ walls or rigid (moment resistant) column-beam connections. Otherwise columns will fail and even reinforcement steel bars will break off (Fig 8). Material tests were conducted in the existing prefabricated structures and some Schmidt Hammer readings were taken. These tests illustrated that strengths of concrete members tested are in accordance with the limitations given in the UBC97. The strength values for concrete qualities suggested in the design, namely C25 and C30, satisfy the empirically obtained strength values. In mechanical and chemical analyses of the construction steel, it was seen that the carbon content considerably exceeded the upper limit, thus giving the reinforced concrete a brittle character.

Following article is given in Turkish Earthquake Code (TEC 2007);

“7.3.4.1 - Special confinement zones shall be arranged at the bottom and top ends of each column. Length of each of the confinement zones shall not be less than smaller 500 mm. Transverse reinforcement with a diameter less than $\varnothing 8$ shall not be used in confinement zones. Along the column, spacing of hoops and crossties shall not be more than 1/3 the smaller cross section dimension and 100 mm, nor shall it be less than 50 mm. Lateral distance between legs of hoops and crossties, a , shall not be more than 25 times the hoop diameter.”

5. FAILURE OF PREFABRICATED CORBEL

Prefabricated beams are supported by corbels on columns. Beams fall as a result of lateral displacement from corbels during earthquakes because of short corbel lengths. (Fig.9) Long corbels are necessary for forming more rigid connections. Long corbel lengths mean long welds and more connection reinforcement bars. Prefabricated bridges on E5 highway, that is on high seismic risk zone, strengthened by adding extra lengths to corbels about 40 cm.

6. PREVENTING LATERAL DISPLACEMENTS

Experiments and observations on earthquake damages prove that RC walls and brick walls reduce lateral displacement and resist shear forces. In prefabricated industrial buildings; lateral displacements must be reduced by cast-in-situ RC walls and brick walls (Fig. 10). Observations that made on Adana and Kocaeli earthquakes show that systems which had brick walls weren't damaged by earthquake loads. Even a 1–1.5 m thick wall prevented failure of column (Atakoy, 2000).

“ 7.12.1.1 – With the exception of single storey industrial-type buildings, prefabricated frame type structural systems with hinge connections (which are unable to resist moments) may be permitted provided that reinforced concrete cast-in-situ structural walls are constructed in both directions to fully resist against the seismic loads “. Although no damage was observed on prefabricated residences, prefabricated industrial buildings were heavily damaged (Fig. 2).

A factory that produces precast structural elements was heavily damaged in Kocaeli earthquake. (Fig. 12) Technician of the factory reported that this factory produced precast structural elements for 23 factories.

Under intensive seismic ground motions, due to the elasto-plastic deformation corresponding to ductility, large lateral displacements form, resulting in the formation of secondary moments. To keep secondary moments at a minimum, inter-storey drifts, in other words, the relative storey displacements, have been limited in TEC 2007. Eq. (1) shows TEC 2007 displacement criteria.



Figure 6. Failure of connection

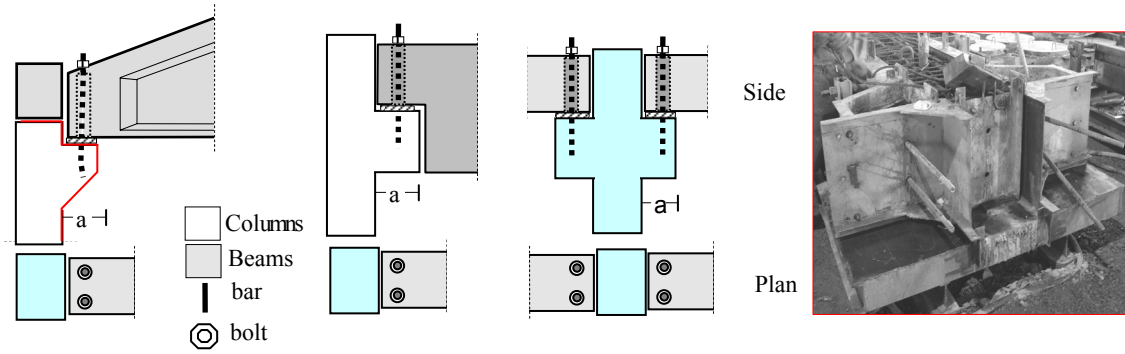


Figure 7. Column-Beam Connections

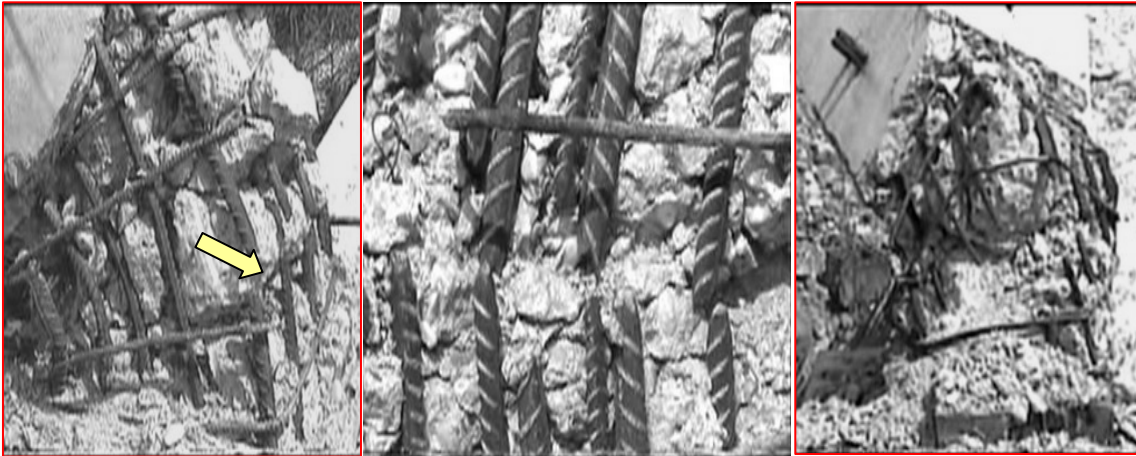


Figure 8. Column damage (Adapazari)

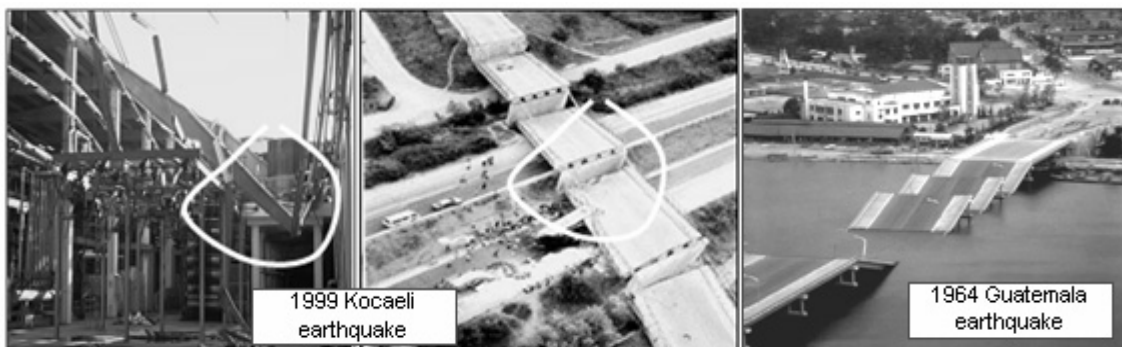


Figure 9. Failure of corbel length and railway

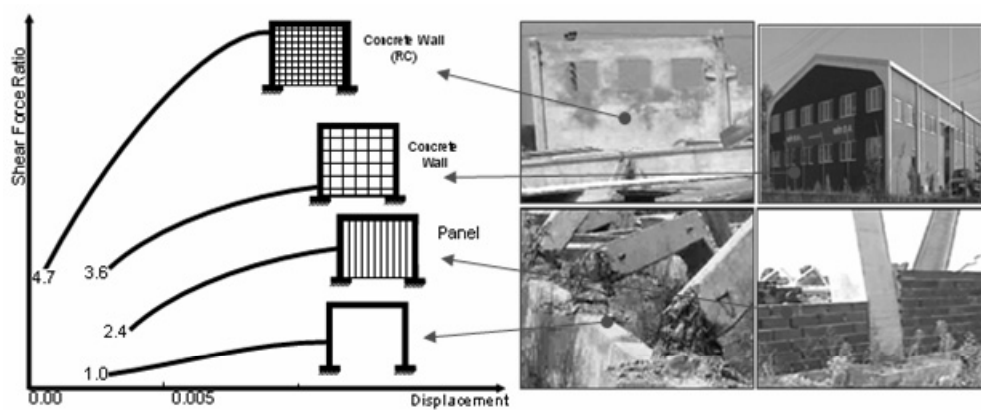


Figure 10. Effects of RC and brick walls on lateral displacement (Ersoy, 1993)



Figure 11. Photographs of RC Wall construction on a prefabricated structure



Figure 12. Prefabricated Structural Element Factory

$$(\Delta_i)_{\max} / h_i \leq 0.0035 \text{ and } (\Delta_i)_{\max} / h_i \leq 0.02 / R \quad (1)$$

Since R-value equals 5 in the buildings where all the earthquake loads are met by single-storey frames (which have fixed supports at basement level, are hinged at the top, and can transmit moments) this limit can be expressed as follows:

$$(\Delta_i)_{\max} \leq (0.0035h, 0.004h)_{\min} \quad (2)$$

The base shear force is computed by using Eqs. (3)

$$V_t = W C = \frac{W A_o I S(T)}{R_a (T)} \quad (3)$$

In Eq. 3, A_o , denoting the effective ground acceleration coefficient, takes the values 0.10 g for the 4th and 0.40 g for the 1st degree seismic risk zones, respectively. I , the structural importance factor, takes values varying in between 1 and 1.5 and is equal to 1 for a conventional reinforced concrete structure. $S(T)$, the spectrum coefficient, is represented by a curve which gives the values of design acceleration spectrum varying with the natural period, T of the structure. In the United States Building Code (UBC 2000), C , the lateral earthquake load coefficient, is computed using the formula:

$$C = \frac{C_v \times I}{R \times T} \begin{cases} C_{\max} = 2.5 C_a \times I / (R \times T) \\ C_{\min} = 0.11 C_a \times I \\ C_{\min} = 0.8 Z \times N_v \times I / R \end{cases} \quad (4)$$

In Eq. (4), Z refers to the earthquake zone coefficient and corresponds to A_o in TEC-2007. The structural behaviour coefficient, R takes the value of 2.2 for prefabricated structures. N_v is the earthquake proximity coefficient which has never been mentioned in the Turkish Earthquake Code. C_v and C_a are velocity and acceleration spectrum coefficients, respectively. In the code [3], for the computation of base shear force

$$V_b = C_b \times W \left\langle \begin{cases} C_d = 2.5 \times A_o \times S / R & T_b \leq T \leq T_c \\ C_d = 2.5 \times A_o \times (T_c / T)^{2/3} / R & T_c \leq T \leq 3 \\ C_d = 2.5 \times A_o \times (T_c / T_b)^{2/3} (T_b / T)^{5/3} / R & T \geq 3 \end{cases} \right\rangle R = k_d k_p R_o \quad (5)$$

Here, W is the total weight of the structure, while C_d stands for the design spectrum coefficient. A_o is the maximum ground acceleration coefficient for design purposes, while S is the ground type coefficient (equal to 1 for medium-class earth, and 0.9 for loose sands and medium clays). k_d , given in the equation, refers to the quality level of structure ductility. In the design computations of structures possessing high ductility, k_d is taken as 1 while for medium-ductility it equals 0.5. k_p , however, is a coefficient related with the locus of joints (connections) and varies between 1.0 and 0.75. TEC 2007 assumes the value of the structural behaviour coefficient, R_o , as 2.0 for prefabricated structures.

7. STRUCTURAL MODEL OF PREFABRICATED BUILDING

A prefabricated structure model is formed using Structural Analysis Program (SAP2000, 2000) similar to prefabricated industrial buildings which are in Adapazari Industrial Complex Zone. Three types of frames are modeled and calculated which are commonly seen in one and two storey industrial buildings in Turkey. Lateral loads are obtained from both TEC and UBC97. These frame models are similar to damaged structural frames during earthquakes (Fig. 13).

After calculations are made, Plane frame system (Type-1) shows the best performance in lateral loads as seen.

8. PRECAST CONNECTIONS

Precast frame are divided into two broad categories,

- Emulated moment frames of precast concrete are those precast beam-column systems that are interconnected using reinforcing and wet concrete in such a way as to create a system that will act to resist lateral loads in a manner similar to cast-in-place system.
- Other than emulated cast-in-place moment frames; frames of this classification are assembled using dry joints; that is, connections are made by bolting, welding, post-tensioning, or other similar means. Frames of this nature may act alone to resist lateral loads, or they may act in conjunction with shear walls, braced frames, or other elements to form a dual system (Fig. 14) (FEMA302 2005).

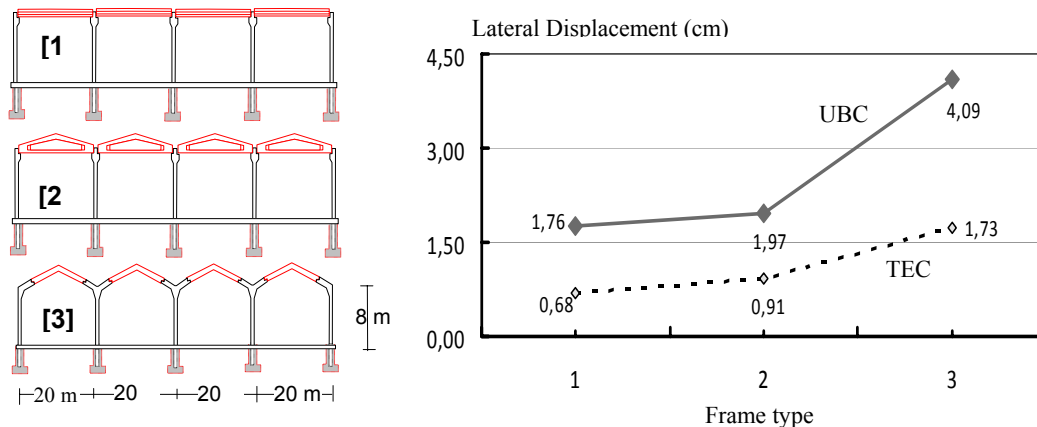


Figure 13. Lateral displacement of prefabricated frame

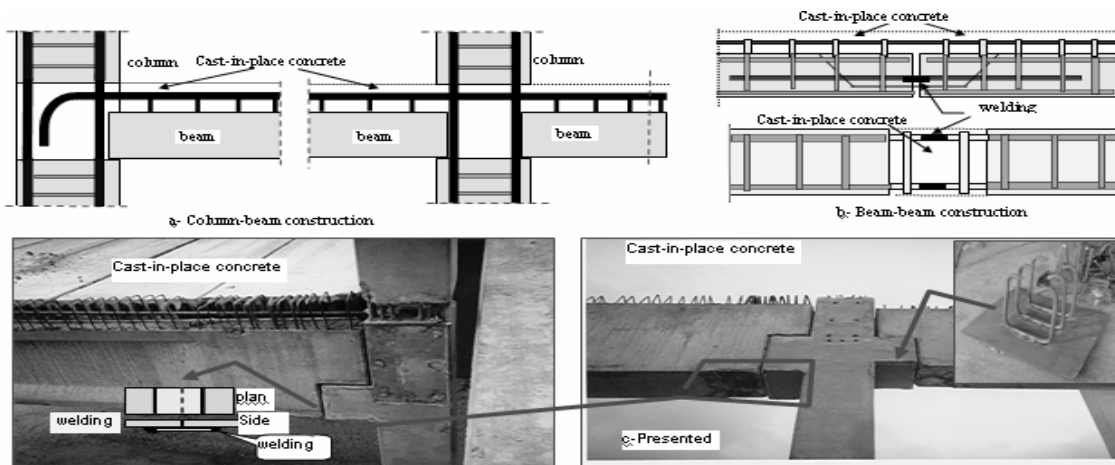


Figure 14. Column-Beam (a) ve Beam-Beam (b) connection (c) presented details

Earthquake strength of a structure changes due to structural element connection's moment resistivity. Rigid connections are moment resistant. These connections are obtained by welding and or cast-in-place concrete (Fig. 15). If system is connected by cast-in-place concrete, its strength must be equal to prefabricated elements concrete strength.

In Fig. 16, the frame has 20 m. spans and a height of 8 m. In this frame, concrete and steel plates are modeled as solids. Solid steel plates are put into structural system in different directions. And also this frame is also calculated as classical cast-in-place RC frame. Seismic loads are calculated by using equations given in UBC97 and TEC. If calculations are examined, it can be seen that structural elements with steel plate supports at sides are subjected to minimum stresses. (Fig. 15b,d) In other connection types stresses reach high values (Fig. 5a,c). In Fig. 16, stresses on connections with steel support at bottom side and corners are examined. Nodes at

the corners are subjected to lower stresses compared to other nodes (Fig. 15f).

In order to obtaining moment resistant connections cast-in-place beams are constructed in prefabricated structures. This increases strength of the structure against lateral and longitudinal loads (Fig. 17). Structural elements share their stresses with other elements by moment resistant connections.

9. FAILURE OF PURLINS AND GUTTER BEAMS

Structures are damaged during earthquakes because of weak sections at purlin-beam connections and long spans lengths (Fig. 17) . Forming ductile system elements by proper stirrup distances will prevent this type of damage.

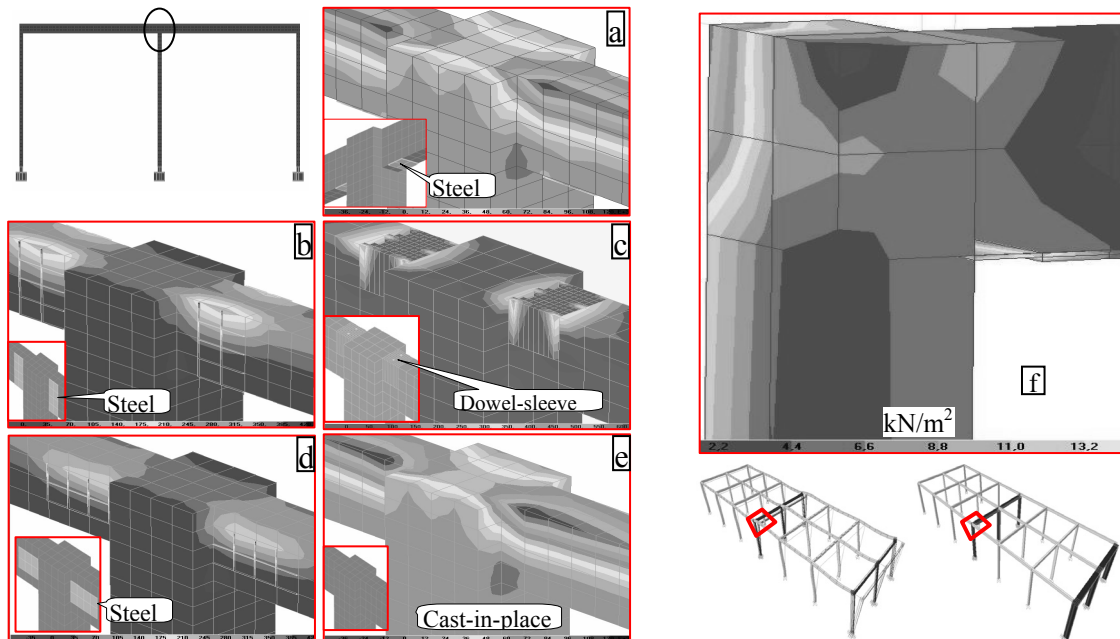


Figure 15. Column-beam connection types calculated with SAP2000



Figure 16. Gutter beam (a) connection section (b) damage

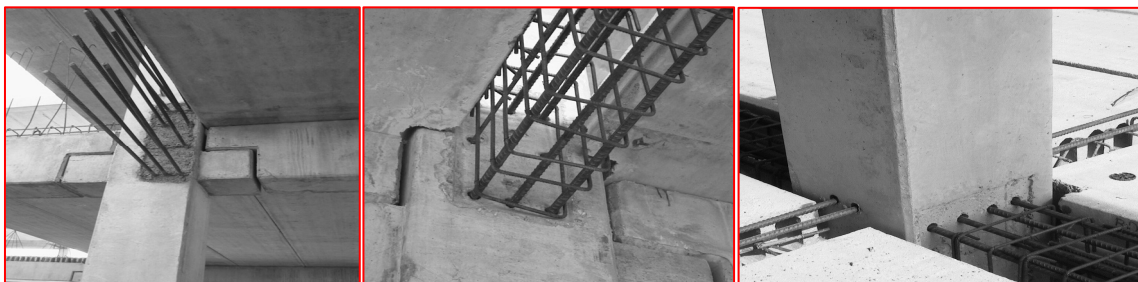


Figure 17. Cast-in-place beam (moment resistant)

In addition, short spans and big purlin sections will help. Gutter beam is a U-shaped beam that empties the water on roof and connects frames in lateral direction (Fig. 17). It also helps to reduce displacements of columns.

Because of crane beams, columns are designed as two spanned elements. This increases lateral displacement and causes heavy damage of columns (Fig. 18)



Figure 18. Two spanned column damage

10. SUMMARY AND CONCLUSIONS

Prefabricated structural systems and all members constituting these systems, as structures constructed using conventional techniques, should satisfy the terms of earthquake-resistant construction such as adequate strength, ductility and rigidity. Nevertheless, the recent earthquakes, i.e., 1998-Ceyhan, 1999-Kocaeli and 1999-Duzce, illustrated that even in the cases where one complies with all the criteria given in TEC problems might occur.

Precast prestressed concrete members with thin concrete sections, often used as exterior curtain walls in commercial and industrial buildings, can be relied upon to act as seismic resistant shear walls. The primary problem in using these walls for seismic resistance is in developing a satisfactory ductile base connection that can transfer forces from the foundation into the thin wall panel. A secondary problem is in meeting existing code criteria for emulation or in proving the capacity of the system.

Earthquake resistivity of industrial buildings is related to

- Moment resistant column-beam connections
- Cast-in-place RC walls which resist earthquake loads
- Proper corbel length (min. short side of column)
- Covering column-beam connection steel bars with grout

- In long spans (20–30 m), column long side (at least 100 cm) must be parallel to beam direction.

“ 7.12.1.1 – With the exception of single storey industrial-type buildings, prefabricated frame type structural systems with hinge connections (which are unable to resist moments) may be permitted provided that reinforced concrete cast-in-situ structural walls are constructed in both directions to fully resist against the seismic loads.” article must be changed and include same requirements for industrial buildings.

Most intensive damages observed in the recent earthquakes on prefabricated industrial structures are those of the single-storey industrial structures with fixed connections at the ground level and hinges at the upper ends. The incompatibility of the structural systems relative to the selected system's inappropriateness with the limits put forward in the Codes regarding lateral rigidity, strength and ductility, raises doubts about the earthquake resistance of these structures. Assembly order must be;

- Columns
- Cast-in-situ RC Walls
- Beams

If beams are assembled before construction of RC walls, structure will fail because of seismic loads at a possible earthquake during construction. Most of our current industrial buildings are constructed according to the old Turkish Earthquake Code old industrial buildings must be repaired. It must remembered

that our industrial structures and economy are under earthquake risk.

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