13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2644

AN EXAMINATION OF DAMAGES OF REINFORCED CONCRETE CONSOLED BUILDINGS IN TURKEY DUE TO 17 AUGUST 1999 KOCAELI EARTHQUAKE

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SUMMARY

An examination of the buildings having structural system deficiencies and damages due to architectural cantilevers is carried out after the 17 August 1999 Kocaeli Earthquake, Turkey. The damage causes are given systematically by considering various structural layouts and the pictures of structures having those of architectural based cantilevers are presented. A number of proposals on rehabilitation and strengthening of the existing buildings are given and discussed in detail. Structural analysis of a consoled building is carried out by considering the elastic behavior and three-dimensional modeling to explain the damage reasons.

INTRODUCTION

The lessons learned from past earthquakes have shown that the earthquake performance strongly depends on the regularity of the structural system in plan and elevation. Regular structures may be defined as those having nearly uniform distribution of story strength, stiffness, weight and geometry throughout their height. In this study, the design deficiencies and behavior of consoled structures that are commonly build in Turkey are presented. Modern codes such as EC 8 [1], UBC [2] and Turkish Code [3] require the regularity as a precondition for an improved seismic behavior. The models based on linear elastic behavior and equivalent static analysis can be sufficient for regular structures, but these analysis methods cannot be adequate for irregular structures. Most of the codes require sophisticated computational procedures, if the structural system is irregular one. Mohle [4] and Mohle and Alarcon [5] are studied the analysis methods and seismic responses of vertically irregular buildings.

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In the building stock of Turkey, consoled buildings have important ratio and there are two types of console building applications that are commonly used. The first type of console buildings is constructed by use of cantilever beams. In this case, the periphery columns of the building are not connected to each other with beams, because the periphery beams are offset to the end of the cantilever beams. Consequently, the periphery frame system of the building cannot be established. In the case of second type of consoled building application, the structural system becomes vertically irregular, due to the axes of the columns around periphery of the building that do not coincide with each other on the ground and the first floors. The columns of these two floors are connected through corbels between two offset columns, although it is not permitted anymore according to the new Turkish Code [3]. Güler [6] is studied the behavior of this kind of a vertically irregular building. The Kocaeli Earthquake of 17 August 1999 affected a wide range of area including the biggest city of Turkey, Istanbul. It was a great laboratory where the reinforced concrete buildings, including those consoled one are tested once and important lessons are learned on the behavior of consoled structures. However, no improvements are done on structural systems of consoled buildings.

In this study, the consoled buildings and their seismic damages in the Kocaeli Earthquake of 17 August 1997 are discussed by considering various structural configurations. The deficiencies of second type of consoled buildings having vertically irregular structural system are discussed in detail as well. Various proposals on rehabilitation and strengthening methods for the existing buildings are given.

CONSOLED BUILDINGS

In the urban planning, the construction area in plan and the number of story of buildings are determined depending on various parameters, such as area of parcel, earthquake activity of the region and soil conditions. To obtain greater area of usage, in Turkey it is customary to arrange architectural consoles over ground floors and consoles are permitted up to 1.5m at the periphery of the buildings. In this case the extensions are produced by arranging either cantilever beams (first kind console) or offsetting the side columns to the periphery of the building and supporting them on corbels (second kind console). In the first kind of designs, architects do not prefer to see beams at the ceiling and the beams of the periphery frames are offset to the end of cantilever beams and the periphery walls are supported on those of beams (Figure 1). This application prevents to arrange regular frames, thus the structure becomes an irregular one. Usually balconies are located at the corners of the building (Fig. 1a). It is common that the earthquake damages of the infill walls are on the cantilever beams that the first kind consoled buildings (Fig. 1) moderate and heavy. Although they are not structural damages, it requires additional repairing costs. Sometimes the parts of the damaged walls can drop and it may cause injuries and even deaths. The general views of two buildings having the second kinds of consoles are given in Figure 2. As it is shown, all the side columns (Fig. 2a) or only corner columns (Fig. 2b) offset to the end of consoles and a vertically irregular structural system is arranged.

DESIGN EXAMPLES OF CONSOLED BUILDINGS

The explanations on structural system deficiencies used commonly are given in various slab plans, sections and pictures of buildings in and around of Istanbul. The first story slab plan of a building collapsed in the Kocaeli Earthquake is given in Figure 3. There are four frames in *y*-direction (the axis *A-G*), while only one regular frame exists in *x*-direction (the axis of *3*). If there were no consoles a frame system could establish through the axis of *1* and *4*. In the present case a significant eccentricity exists between the mass and rigidity centers which may produce large torsional effects, when the system is subjected to an earthquake. As it is seen, the main reason is the lack of a frame system due to the consoles.

This arrangement is generally produced, because the structural engineers tent to fulfill the design needs of architects. The layout and elevation of a five-story building is given in Figure 4. As it is seen, the building has two kinds of consoles, cantilever beams through the axes of *1* to *8* on the right side and the corbels on the left side of the building. Over the level of second floor, no frame system exists along the short and long directions. The regular frame system is only established at the ceilings of the first and second stories and no any regular frame system exists at other stories. It is not easy to predict the behavior and the failure modes of that building under lateral loads. Slab plans and damaged pictures of a five-story building are shown in Figure 5. The closed consoles are arranged on the left and right sides of the building and a number of beams are usually supported indirectly and there is almost no frame on the axis between *A* and *G* (*y* direction). Frames are arranged between the axis of *G* and *O* and the center of rigidity is probably around the axis of *J*. It means that the torsional stiffness of the building is quite poor around the axes of *A* and *O*, while various regular frames are established between axes of *1* and *10* (*x* direction). During the Kocaeli Earthquake, the part of the building the axes between *A* and *F* (left part) were collapsed, while other part was still standing without heavy damages on the structural system. It is obvious that the reason of the building is not only due to the structural deficiencies, but also poor material (concrete) quality and workmanship of reinforcement decrease safety of the system. However, in the present case the dominant effect was torsion (eccentricity between the mass and the rigidity centers of the building was quite greater).

STRUCTURAL ANALYSIS OF A BUILDING HAVING SECOND TYPE CONSOLE

The building analyzed is a five-story reinforced concrete structure consisting of an orthogonal frame system [6]. The layout of the ground floor and the elevation of the building are shown in Figure 6. As it is shown in the plan and elevation of the building, the axes of the columns around the periphery of the building do not coincide with each other on the ground and first floors. The columns on the corner and on the perimeter in plan of these two floors are connected with corbels, which makes the structural system vertically irregular one. However, the inner columns of the building are continuous from the ground floor to the top floor. The story heights are *3.00m* and the slab thickness is *0.12m*. The cross section of the frame beams is *0.25m/0.60m* and the columns are $0.45m\times0.45m$ and $0.45m\times0.55m$ (ground floor), $0.45m\times0.45m$ and $0.35m\times0.45m$ (*1.st 2.nd* and *3.th* floors), $0.30m\times0.30m$ (*4.th* floor). The corbels have a height of *0.40m* and *1.50m* at the tip and at the connection points to column, respectively. The static and dynamic numerical analysis is carried out by using the SAP 2000 package and assuming linear elastic behavior. For the structural system, the modulus of elasticity is considered as $28\times10^6\ kN/m^2$. The structural system of the building is considered as space frames having shell elements representing floors. The columns are assumed to be fixed at base. Additionally, a separate analysis is done by assuming the elastic support at the base. In the case of elastic support the columns are assumed to be supported by square footings on the elastic springs representing the soil. A summary of the results of the analysis is presented below:

The free vibration periods of the structure for the cases of the fixed and elastic support are given in Table 1. The masses of the columns, the beams, the partition walls and the floors are assumed to be lumped at the joints of the beam and the column. As it is expected, the periods of the building increase when the elasticity of the soil is included.

Table 1. Free vibration periods of the first ten modes (FB:fixed base, EF:elastic foundation; sub grade modulus of soil, K=10^5 kN/m^3)

Number of Modes	*1.*	*2.*	*3.*	*4.*	*5.*	*6.*	*7.*	*8.*	*9.*	*10.*
FB; T(s)	*0.576*	*0.558*	*0.498*	*0.221*	*0.220*	*0.138*	*0.134*	*0.097*	*0.093*	*0.068*
EF; T(s)	*0.618*	*0.595*	*0.525*	*0.228*	*0.227*	*0.145*	*0.142*	*0.130*	*0.102*	*0.094*

Under vertical dead and live loads, internal forces in the structural system of the building are obtained. In the static solutions, internal forces are evaluated only for the service loads (G+Q) by considering various arrangements of the loading patterns. However, for the sake of brevity only limited number of internal forces of structural elements are given in Table 2; the elements of axes *A, C* and *5, 7* are in *x* and *y* directions, respectively, where *V* denotes shearing force, *M* bending moment and *T* is torsional moment in the corbels and the beams around their main axes. Because of the three dimensional frame and shell element model is adopted, the interaction between the frames is taking into account. The results show that the torsional effect of the corbels has a profound effect on the internal forces and the moments. The dynamic analysis of the structural system is carried out by using two methods: equivalent static method and response history method. In order to obtain the design forces for dynamic case, the Turkish Seismic Code [3] is used. As it is known, the total base shear force depends on the seismic zone, the soil conditions, the structural system and the building importance coefficient. For the present building the base shear is evaluated as $V_t=1350\ kN$ and its vertical distribution is obtained accordingly. The internal forces of the structural system under base shear force are obtained for x and y directions separately and some of the internal forces are given in Table 2. The response of the building to a strong ground motion of Erzincan (Turkey) Earthquake of March 1992 is obtained by using a linear dynamic analysis. The solution is evaluated by considering the first ten free vibration modes of the building by use of Ritz approximation. In the solutions the damping coefficient is assumed to be *0.05*.

Table 2. Internal forces in some elements under the static loads (G+Q) and the equivalent static force procedure (E; earthquake)

Elements (axes)	*V (kN)*			*M (kNm)*			*T (kNm)*		
	G+Q	E (x-x)	E (y-y)	G+Q	E (x-x)	E (y-y)	G+Q	E (x-x)	E (y-y)
C/(5-6)	*119.8*	*2.9*	*46.6*	*239.2*	*8.2*	*112.0*	*0.8*	*0.6*	*0.00*
C(6-7)	*433.6*	*-14.1*	*69.6*	*513.4*	*17.8*	*109.8*	*4.0*	*34.1*	*3.1*
B/(5-6)	*73.0*	*10.4*	*36.8*	*156.5*	*32.9*	*94.1*	*1.6*	*0.1*	*1.1*
B/(6-7)	*294.7*	*66.4*	*9.1*	*339.2*	*73.6*	*88.9*	*62.2*	*11.5*	*9.2*
5/(C-B)	*117.4*	*50.9*	*4.4*	*238.6*	*120.7*	*11.9*	*0.6*	*0.1*	*0.4*
5/(B-A)	*435.9*	*78.2*	*14.4*	*515.8*	*123.0*	*19.1*	*2.9*	*0.8*	*29.6*
6/(C-B)	*71.8*	*41.0*	*12.4*	*155.6*	*103.5*	*37.4*	*1.5*	*1.1*	*0.2*
6/(B-A)	*293.8*	*64.3*	*62.3*	*338.1*	*96.0*	*70.3*	*62.3*	*11.4*	*8.8*

In various seismic codes, the importance of vertical component of earthquake is stressed especially for vertically irregular structures. The equations for estimating peak vertical acceleration and vertical absolute acceleration response spectra in the seismically active part of Europe and the adjacent areas were analyzed by Ambraseys and Simpson [7]. They reported that the vertical spectral values are about *1/2-1/4* of the horizontal ones and this ratio depends on the distance from the source. For the seismic response of the consoled building discussed above, the Erzincan Earthquake 1992, March 13 is used according to Euro Code 8 [1] as follows:

$E_x+0,3E_y$ $\quad$ $0,3E_x+0,3E_y+E_z$ $\quad$ $E_x+0,3E_y+0,3E_z$

$0,3E_x+E_y$ $\quad$ $0,3E_x+E_y+0,3E_z$; (1)

where E_x, E_y and E_z; represent the earthquake effects in *x, y,* and *z* directions, respectively. In the solutions, the east-west component of the earthquake is applied to *x* direction and the north-south component to *y* direction. The internal forces are obtained and given in Table 3 for some of the combinations of the earthquake considering the fixed base supporting. Variations of the shear base forces different load combinations are given fixed base in Table 4.

Table 3. Internal forces in some elements under Erzincan 1992 (Turkey) Earthquake of ($E_x+0.3E_y+0.3E_z$) (C1); ($0.3E_x+E_y+0.3E_z$) (C2); ($0.3E_x+0.3E_y+E_z$) (C3) combinations.

Elements (axes)	V (kN)			M (kNm)			T (kNm)		
	C1	C2	C3	C1	C2	C3	C1	C2	C3
C/(5-6)	56.8	16.7	17.4	136.1	40.1	42.7	0.2	0.3	0.2
C(6-7)	86.8	29.2	39.4	133.3	43.4	54.3	8.1	26.4	8.8
B/(5-6)	46.2	14.6	13.6	116.4	40.4	35.0	12.6	0.4	0.4
B/(6-7)	71.7	60.3	29.4	105.1	69.9	38.9	12.3	8.5	5.9
5/(C-B)	13.7	42.3	14.5	33.6	101.2	36.0	0.4	0.2	0.8
5/(B-A)	26.1	67.0	33.8	38.1	102.6	44.4	36.7	11.1	10.5
6/(C-B)	14.8	34.7	12.0	41.4	88.3	31.5	0.4	0.9	0.4
6/(B-A)	72.3	59.1	29.4	81.0	85.2	37.1	13.1	8.6	5.1

Table 4. Base shear forces for different loadings for the fixed base.

External effect	V_x (kN)	V_y (kN)	V_z (kN)
$E_x+0.3E_y$	1704	346	-
$0.3E_x+E_y$	512	1148	-
$E_x+0.3E_y+0.3E_z$	1704	345	227
$0.3E_x+E_y+0.3E_z$	511	1148	227
$0.3E_x+0.3E_y+E_z$	512	345	227
Equivalent static force	1350	1350	-

An important subject is to determine the number of modes to be included in the numerical calculations. The problem is studied by Lopez and Cruz [8] considering regular buildings under horizontal earthquake effect. In regulations of EC 8 [1] and UBC [2], the numbers of modes are given according to the effective mass ratio and number of story of the building. It is observed that the mode number is high when the vertical component of earthquake is considered. The numerical solutions performed for the consoled building show that the equivalent static force analysis yields more large values to be considered in the design almost for the all frame elements. The axial force of the columns increases when the vertical seismic action is considered. However, the increase is quite small. At least for the present building, one can deduce that the effect of vertical earthquake can be negligible.

DAMAGE PATERNS

The Kocaeli Earthquake of August 17, 1999 was the first severe earthquake caused serious damages on the second kind of consoled structures in Turkey, especially in Istanbul. The deficiencies of structural layout, poor material, workmanship and irregularity in the structural systems are the main reasons of damages. Detailed definitions and provisions on regularities of structures in plan and elevation are given in Turkish Code. The design of second kind consoled buildings is not permitted. The corner columns of the two buildings damaged in 17 August 1999 Kocaeli Earthquake is shown in Figure 7a and 7b. The abrupt change in rigidity of the ground story changed the distributions of shear forces and the short column parts (the part between the corbel and the bottom end of the column) could not carry the additional shear forces due to by the torsional effects, consequently typical shear failure is developed just after the earthquake the damaged column (Fig. 7b) is temporarily strengthened. No damages detected at the corbels or at the inner beams connected to the corbels. It indicates that the main cause of the damage is deficiencies in the structural system and the existence of the short column. Moreover, poor material quality and workmanship of the reinforcement (including 90 degrees arrangement of stirrups) can be mentioned as the other main damage reasons.

STRUCTURAL SYSTEM IMPROVEMENTS AND STRENGTHENING

In the case of the second type irregularity (vertically irregular system due to the discontinuity at the columns on the periphery) it is recommended to improve the behavior of structural systems by strengthening, even if slightly or no damages exist. Two possible alternatives are presented in Figure 10. In transferring the axial loads to the ground floor columns directly, a few different techniques can be chosen. One of them is addition of new columns to the end of corbels or arrangement of shear walls including the corbels. The other is converting the load path to the direct one and eliminating the existing irregularity. If the corner or the side columns of the building are supported at the tip of the corbels. They can be jacketed down to the foundations. If addition of shear walls at the level of ground floor is not permitted, only columns can be built at the tip of the corbels such as given in Figure 10 b. Depending on the lateral stiffness of the entire structural system of the building, more shear walls can be added and more columns can be jacketed. The strengthening design of a consoled building designed by Altan and Aydogan [9] is presented in Figure 11. The structural layouts of the ground and the first stories are given in Figure 11a) and 11b). The shear walls having L cross section at the corners are used to convert the load path to the direct one and to strengthen whole structural system. To ensure the integration of the new and the existing structural systems can be accomplished, the corresponding drawing details must be prepared carefully and the application has to be done accordingly. In the structural systems having vertical irregularity loads are transferred directly by avoiding unnecessary supports.

CONCLUSIONS

This paper deals with damages due to irregularities in the structural system including the recent earthquake. Special attention is drawn to the problems of the irregular structures and design deficiencies, strengthening and improvement in the structural system and discussed in view of vertically irregular structural system. Furthermore, attention on arrangement of corbels and adjoining beams and geometrical discontinuities of structural elements are focused and various numerical calculations are carried out to determine the effect of vertical irregularity on the behavior of the structural system. It is stressed that special considerations in detailing of corbels and inner beams should be given for providing acceptable seismic behavior. The numerical results show that especially corner columns of the ground floor should be designed carefully for torsional effects at the joint of the corbel. It is the opinion of the authors that the vertical component of the earthquake should be taken into consideration in the design of consoled buildings. The numerical analysis shows that the vertical ground motion excites higher modes in the vertically irregular building compared to the regular buildings. The authors of this paper believe that some structural system improvements and strengthening applications must be done to improve the earthquake performance that kinds of consoled buildings. Otherwise, these buildings will be having high potential damage in the existing building stock of Turkey. The authors recommend that the configuration of the regular frame system should be provided; otherwise construction permission should not be given.

Finally, following general conclusion can be expressed:

1) The systems having offset columns should be avoided as possible. When it is not the case, then the arrangement of the joint where column and corbel and inner beam connect should be done with extreme care in analysis as well as in application.

2) The static and dynamic analysis which is carried out by computer programs must be used carefully, because some of the details of structures cannot be modeled sufficiently for the computer programs. Although the dynamic elastic analysis is mathematically attractive, the equivalent static analysis for the irregular structure is of prime importance.

3).The vertical seismic action increases the axial forces of columns however, the difference is negligible. Since the vertical component of the earthquake excites higher modes, the number of modes to be included in the analysis should be increased. In this respect for the presented numerical results Euro Code 8 yields good results for the participation mass.

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a) b)

Figure 1 General view of two buildings having first kind of consoles damaged (a) moderately, (b) heavily

Figure 2 General views of two buildings having second kind consoles

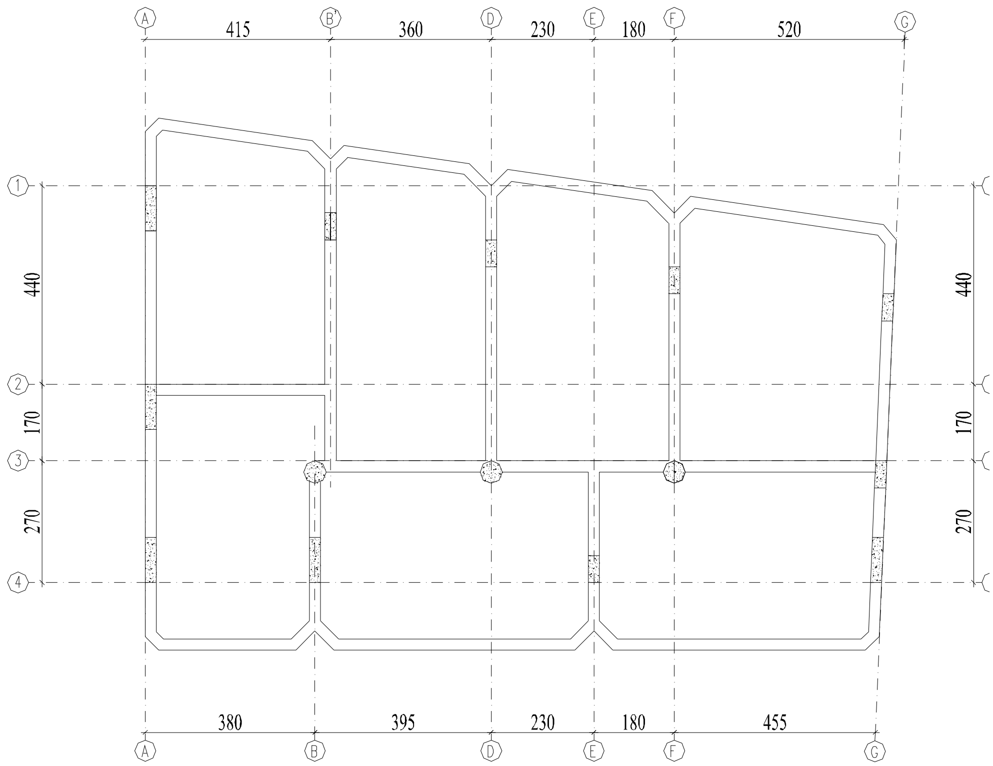
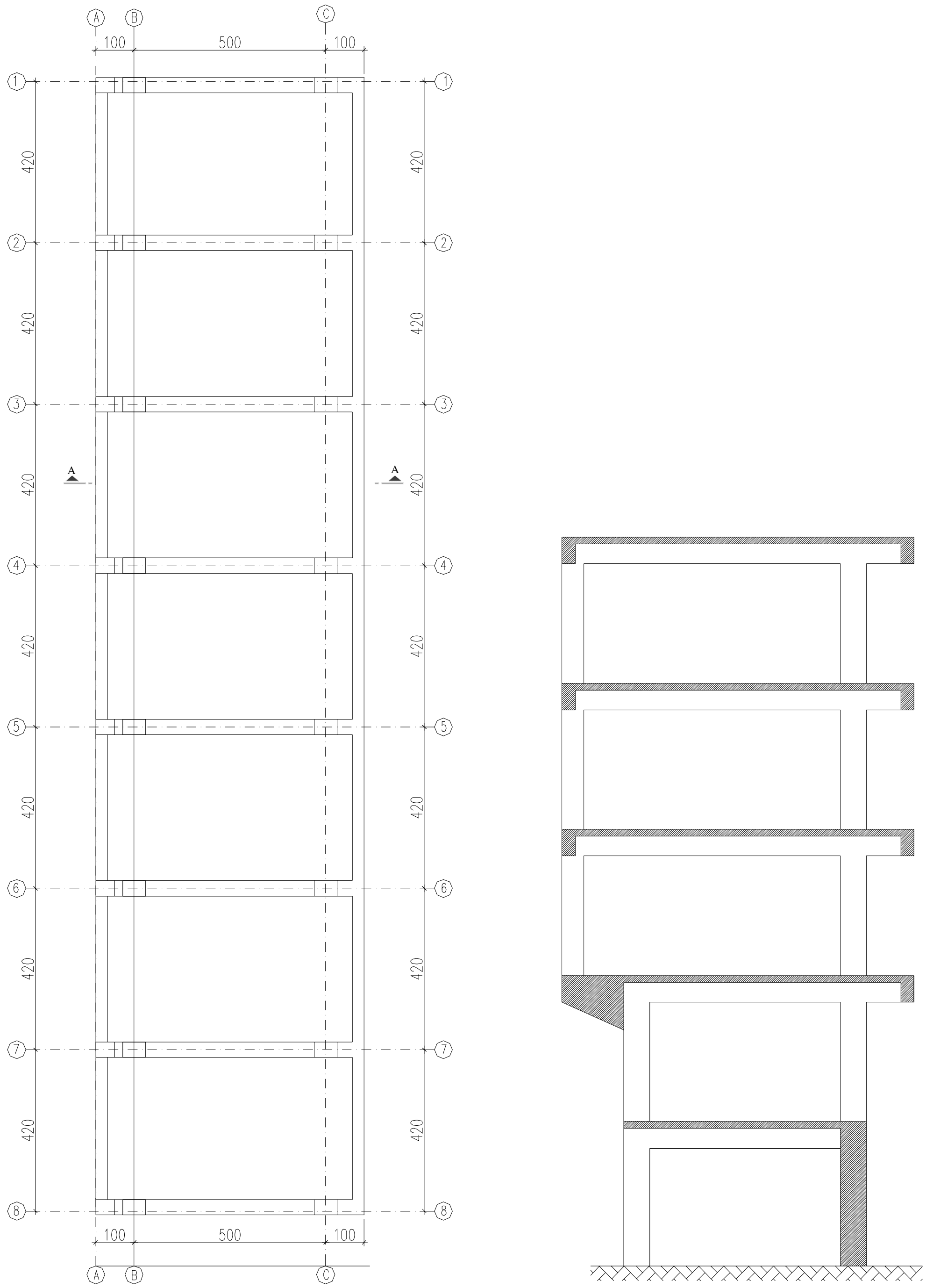


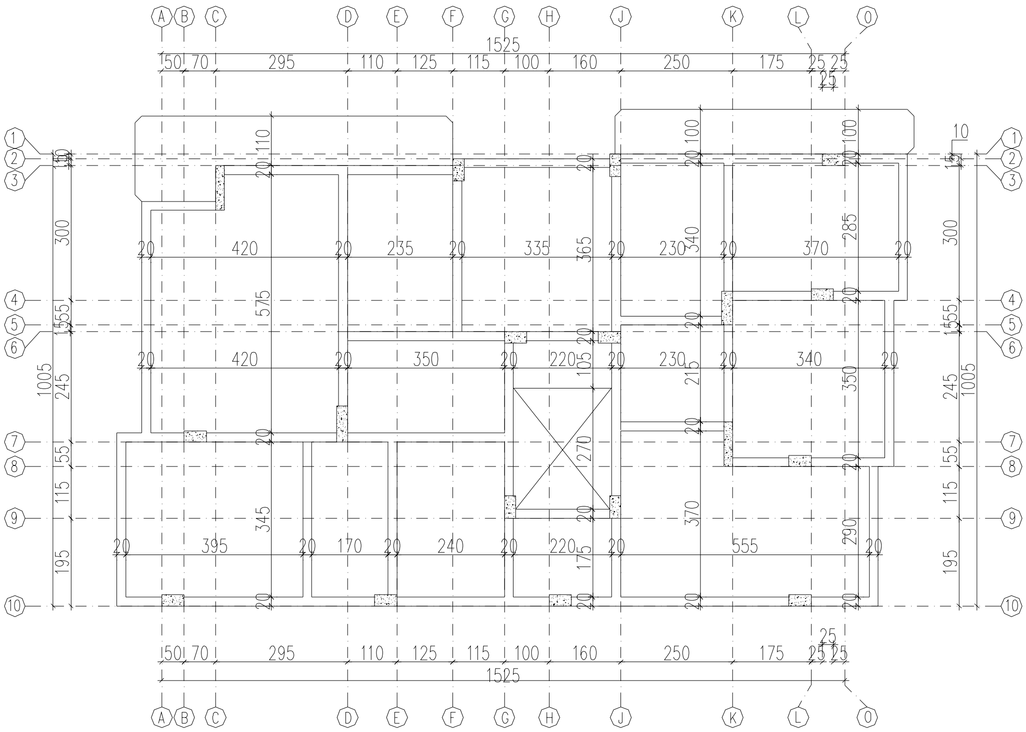
Figure 3 Structural layout and deficiencies in the frame system



(a)

(b) A-A

Figure 4 a) Structural layout b) elevation of building of five stories having two kinds of consoles



a)

b) **c)**

Figure 5 (a) Structural layout of the building of four stories, and (b,c) the same building after the earthquake

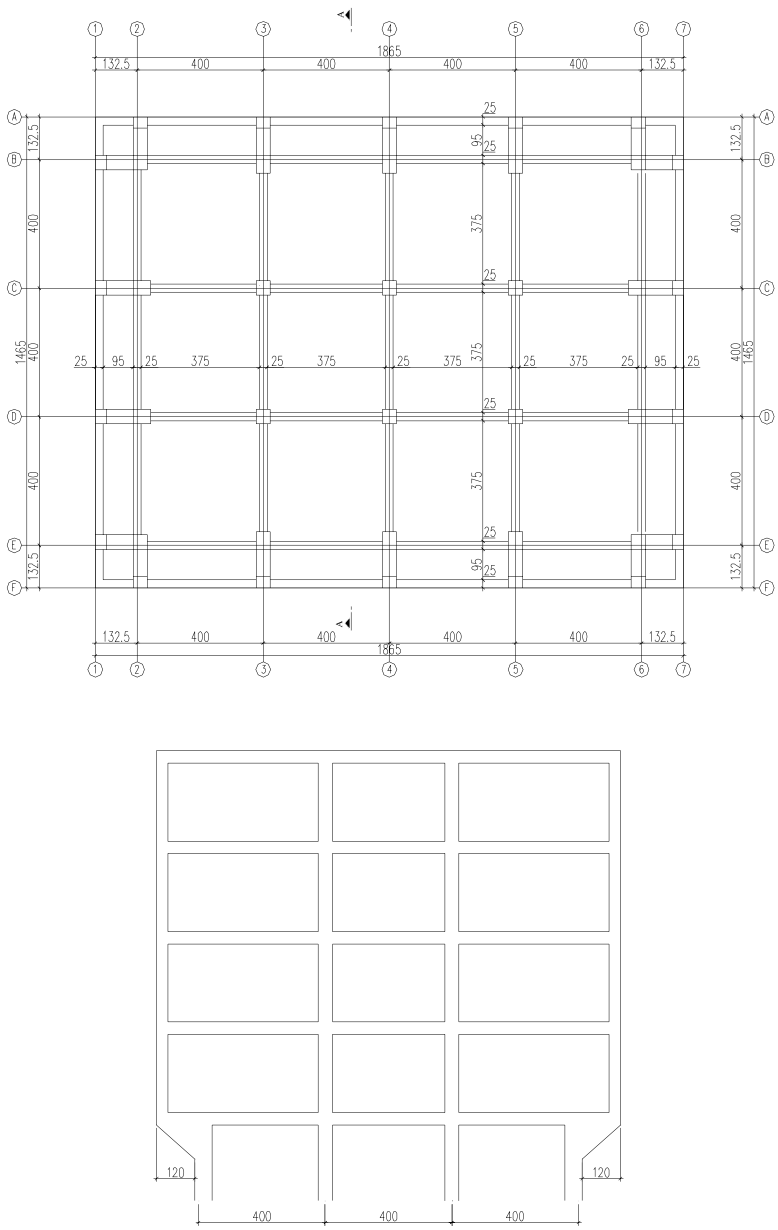
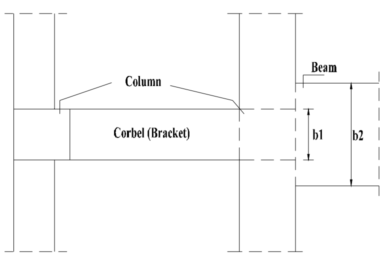


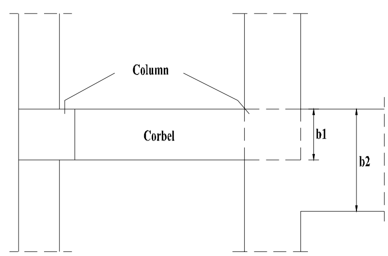
Figure 6 (a) Structural layout and (b) elevation of a building of five stories

Figure 7 Corner columns damaged heavily connected corbels in two directions (shear failure)



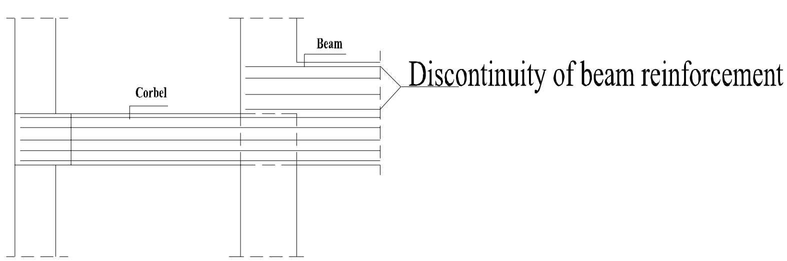
a) b1: Assumed width of the beam by the computer

b2: Real width of the beam



b) b1: Assumed width of the beam by the computer

b2: Real width of the beam



c)

Figure 8 (a, b) Layout of corbel and internal beam connection and (c) discontinuity of reinforcement at the joint

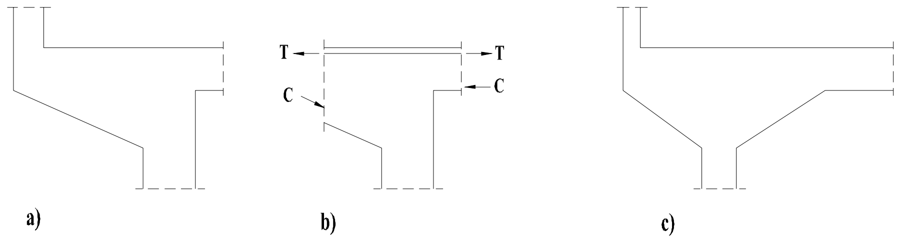


Figure 9 Elevation of corbel and internal beam (a) discontinuity, (b) unbalanced internal forces and (c) improved arrangement of the joint

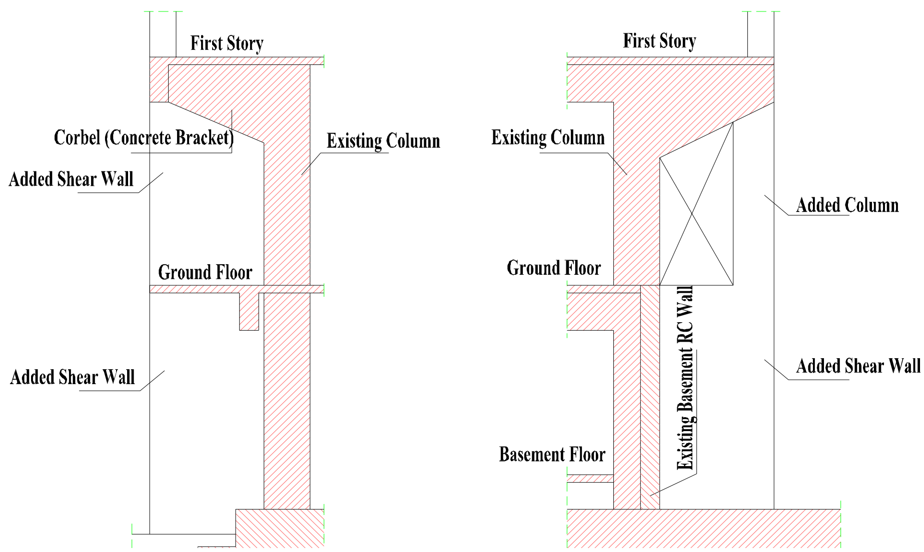
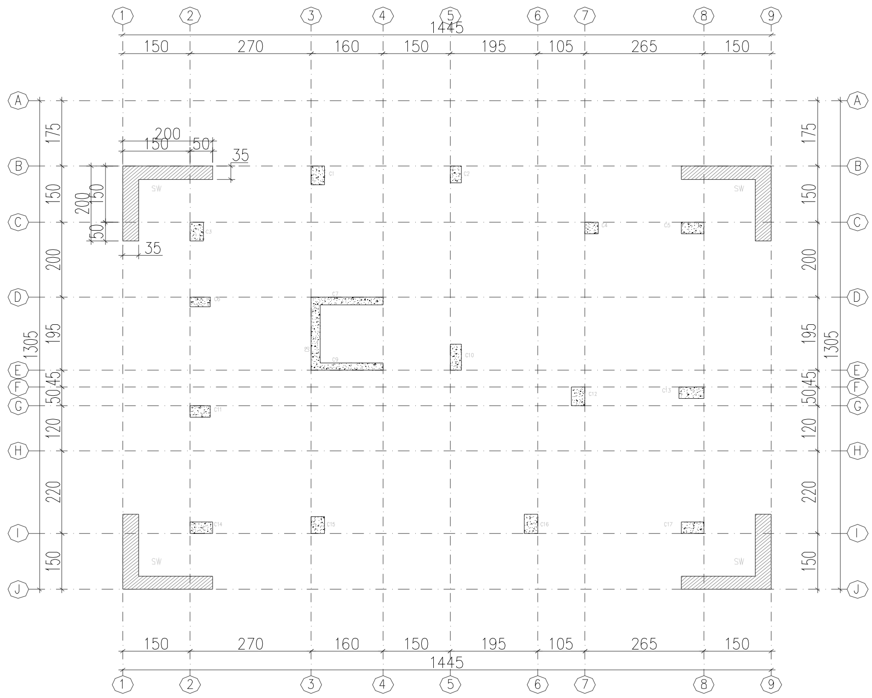
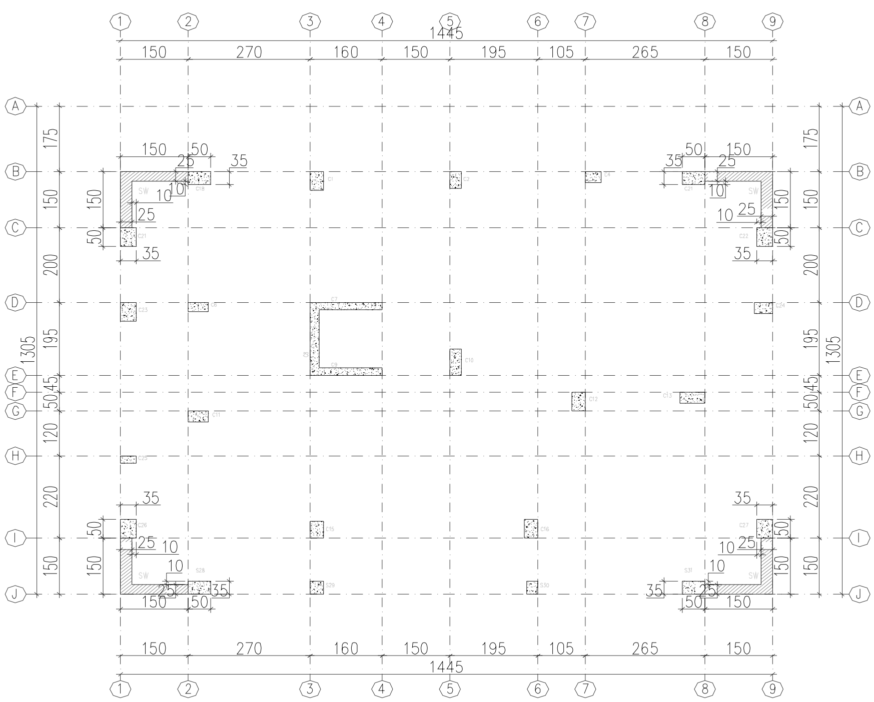


Figure 10 Strengthening examples for the second kind consoles: (a) adding shear wall, (b) adding column to the tip of the corbel



a)



b)

Figure 11 (a) Ground and b) first story floor plans of a building strengthened by shear walls of L cross section at the corners