OPTIMUM ALTERNATIVE TO REDUCE COLUMN SIZE CONSIDERING BEHAVIOR AND COST IMPACTS ON BUILDING

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ABSTRACT

The increasing of high raise and heavy industrial construction industry causes increasing in structural columns loads and accordingly their cross sections, on other hand; architectural and mechanical requirements limit the available spaces for columns. Commonly, three alternatives are used to reduce column size to fit into the available space with same axial capacity, the first is to use higher concrete strength, the second is to use composite column (enclosed or in-filled) and the third is to use high strength steel column. In this research, a parametric study is carried out to figure out the impact of each alternative on the structural behavior and direct cost of the project. The study is based on average materials, labor and equipment rates in USA in 2016. Study results indicated that optimum alternative is to use higher concrete strength up to 1.4 times the concrete strength of floors beyond this limit, composite column (enclosed or in-filled) is recommended. Finally high strength steel column is the only alternative for very compacted columns.

Keywords: RC Column, Composite column, Steel column, Size reduction, Cost impact

1. INTRODUCTION

Reducing columns sizes is one of the common architectural demands especially in high raise and heavy industrial buildings. In order to reduce the cross section of column, the allowable compressive stress of its material should be increased. There are three alternative methods to increase the allowable compressive stress, the first is to enhance the quality of original material, the second is to use stronger material and the third is to use combination of original material and stronger material. Each one of those alternatives has an impact on the structural behavior, construction time and direct cost of the project. The aim of this research is to study the impact of each one of those alternatives on the project. Results of study will be analyzed and discussed to select the optimum alternative.

2. RESEARCH PROGRAM

The research is based on parametric study for three groups with four alternatives in each group besides the original normal strength reinforced concrete design. The first group is to reduce the cross section area of column to about 70% of the original section; second group is to reduce the cross section area of column to about 50% while the third group is to reduce the cross section area of column to about 30% of the original section. In each group, four alternative designs were studied; those alternatives are high strength reinforced concrete column, enclosed composite column, in-filled composite column and high strength steel column. Table (1) shows graphical presentation for the parametric study program.

In order to carry out a fair comparative study, each one of the nine columns was designed considering the following points:

- Cross sections of all columns are symmetric about the two principal axes
- All columns have the same ultimate compressive capacity
- All columns have the same fire rating
- Alternative columns in each group have the same architecture dimensions.
- All reinforcing bars meet ASTM A615 Grade 60
- All steel sections meet ASTM A572 grade 50

The thirteen columns will be compared from the following point of views:

- Column strength
- Ultimate compressive capacity
- Ultimate flexural capacity

- Column stiffness
- Axial stiffness
- Flexural stiffness
- Required construction activities
- Direct cost of one meter of column

"CSI Section Builder" software was used to calculate the ultimate compressive and flexural capacity of each column by drawing its interaction diagram. The calculation is carried out based on simple parabolic stresses distribution in concrete section and perfect plastic behavior of reinforcement bars and steel sections.
The Ultimate compressive capacities of all columns should almost be the same (as considered in section design) on other hand; ultimate flexural capacities are different and represent column ability to resist lateral loads.
Column stiffness is calculated using ACI-318 as follows:

Equivalent axial stiffness (EA) $= 0.2\ Ec\ Ac + Es\ As$ ………… (1)
Equivalent flexural stiffness (EI) $= 0.2\ Ec\ Ic + Es\ Is$ ………… (2)

Where: Ec, Es are the elastic modulus of concrete and steel respectively, Ac, As are the areas of concrete and steel section respectively and Ic, Is are the second moment of inertia of concrete and steel sections about the principal axe respectively.
Number of required activities to construct the column is a good indication for construction complexity, construction time and also the indirect cost. Generally, reinforced concrete column requires four activities (formwork, installing reinforcement, casting and curing). Embedded steel column requires only one activity (erection) while exposed steel column requires three activities (erection, anti-rust painting and fire protection).
In order to compare the direct cost of each alternative, detailed quantity survey was carried out to calculate amount of materials and activities required for one meter length of each column. Rates of materials, labor and equipment were extracted from "2016 National Construction Estimator – 64th Edition". Those rates are the average rates in USA and Canada in US dollars.

3. PARAMETRIC STUDY

Descriptions of each column in this study are summarized as follows:
COL-100% (Original design): Normal strength reinforced concrete column (Fc'=25 MPa) with cross section of 1000x1000 mm. 20T25 Longitudinal bars and 3 sets of ties T10-150.

COL-70%-1: Normal strength reinforced concrete column (Fc'=35 MPa) with cross section of 850x850 mm. 16T25 Longitudinal bars and 3 sets of ties T10-150.

COL-70%-2: Enclosed composite column consists of normal strength reinforced concrete column (Fc'=25 MPa) with cross section of 850x850 mm. 16T25 Longitudinal bars and 1 set of ties T10-150 and embedded steel section of 2 IPE 600. The chosen steel section is more than required to achieve required capacity but it is used to satisfy the minimum $(As/Ac) \geq 4\%$.

COL-70%-3: In-filled composite column consists of square hollow high strength steel section 750x750x18 mm filled with normal strength concrete (Fc'=25 MPa) reinforced with 12T25 Longitudinal bars. The column is covered with 50mm thick fire protection layer to satisfy the fire rating. The total architectural dimension (including fire protection cover) is 850x850 mm. The chosen steel section is more than required to achieve required capacity but it is used to satisfy the minimum $(t/b) \geq \sqrt{(Fy/3Es)}$.

COL-70%-4: High strength Steel section 2 IPE 750x210, column dimensions are 775x775 mm. The column is covered with 50mm thick fire protection layer to satisfy the fire rating. The total architectural dimension (including fire protection cover) is 875x875 mm.

COL-50%-1: High strength reinforced concrete column (Fc'=50 MPa) with cross section of 700x700 mm. 20T25 Longitudinal bars and 3 sets of ties T10-150.

COL-50%-2: Enclosed composite column consists of normal strength reinforced concrete column (Fc'=25 MPa) with cross section of 700x700 mm. 12T25 Longitudinal bars and 1 set of ties T10-150 and embedded steel section of 2 IPE 550.

COL-50%-3: In-filled composite column consists of square hollow high strength steel section 600x600x14 mm filled with normal strength concrete (Fc'=25 MPa) reinforced with 12T25 Longitudinal bars. The column is covered with 50mm thick fire protection layer to satisfy the fire rating. The total architectural dimension (including fire protection cover) is 700x700 mm.

COL-50%-4: High strength Steel section 2 HEB 600, column dimensions are 600x600 mm. The column is covered with 50mm thick fire protection layer to satisfy the fire rating. The total architectural dimension (including fire protection cover) is 700x700 mm.

COL-30%-1: High strength reinforced concrete column (Fc'=70 MPa) with cross section of 550x550 mm. 16T32 Longitudinal bars and 2 sets of ties T10-150.

COL-30%-2: Enclosed composite column consists of normal strength reinforced concrete column (Fc'=25 MPa) with cross section of 550x550 mm. 12T25 Longitudinal bars and 1 set of ties T10-150 and embedded steel section of 2 HEB 360.

COL-30%-3: In-filled composite column consists of square hollow high strength steel section 450x450x24 mm filled with normal strength concrete (Fc'=25 MPa) reinforced with 12T25 Longitudinal bars. The column is covered with 50mm thick fire protection layer to satisfy the fire rating. The total architectural dimension (including fire protection cover) is 550x550 mm.

COL-50%-4: Square hollow high strength steel section 450x450x32 mm. The column is covered with 50mm thick fire protection layer to satisfy the fire rating. The total architectural dimension (including fire protection cover) is 550x550 mm.

Table (2) shows summary for parametric study data and section proprieties of each alternative besides used materials, labor and equipment rates.

4. RESULTS ANALYSIS AND DISSECTION

Table (2) summarized all results of the parametric study; it includes capacities, stiffness, quantities, activities and direct cost of each alternative besides the original design. Study results indicated the following;

1) Capacities

a. Although all alternatives have almost same ultimate compressive capacities (±2%), their ultimate flexural capacities (Mu90, Mu50) are completely different, but proportion with column size.
b. Heavy axially loaded concrete column (P = 90% Pu) can resist some bending moment, this moment reduced with reducing concrete percent in composite column and equals zero for pure steel column, refer to interaction diagrams in figures (1), (2) and (3)
c. For all columns, ultimate resisting moments at (P= 90% Pu) are less than those at (P= 50% Pu). Also the ratio (Mu90 / Mu50) is independent from column size.

2) Stiffness

a. For concrete columns, both axial and flexure stiffness are in proportion with column size.
b. For both composite and steel columns, the axial stiffness is almost independent from column size because only one fifth of concrete stiffness is considered.
c. For both composite and steel columns, the flexural stiffness is function of the second moment of inertia of steel section (and accordingly the size of column)
d. Generally, both axial and flexure stiffness of all alternatives are than the original design.

3) Activates

a. Generally, concrete columns required three activates, formwork, installing re-bars and casting.
b. Enclosed composite columns requited one more activity which is steel section erection.
c. In-filled composite columns don't required formwork, but they required anti-rust coating and fire protection.
d. Steel columns required three activates, steel section erection, anti-rust coating and fire protection.

4) **Quantities**

a. Generally, volume of concrete reduces with increasing the characteristic strength (Fc').
b. Formwork, anti-rust coat and fire protection areas increased with increasing column size.
c. Weight of re-bars depends on both reinforcement present independent (Ar/Ac) and column size.
d. Weight of steel column depends only on the axial capacity independent from column size.

5) **Direct cost**

a. For concrete columns, direct cost decreases with increasing the characteristic strength (Fc').
b. All composite and steel alternatives are more expansive than their equivalent concrete columns.
c. For low reduction percent of column size, the enclosed composite column is cheaper than its equivalent in-filled one, but in high reduction percent of column size, both of composite columns have almost same cost because concrete contribution in column capacity and cost is minimized.
d. Steel column is the most expansive alternative, since the weight of steel column depends only on the axial capacity; the cost of steel columns is almost independent from column size.
e. Figure (4) shows the relation between direct cost and average axial stress ($Pu/size^2$) for all alternatives. Dashed lines represent the direct cost in case of ignoring the minimum code requirements for composite columns (minimum plate thickness for in-filled composite column, and minimum (As/Ac) for enclosed composite column).

From previous notes, the optimum alternative based on cost point view could be selected based on the following:

1) Increasing the characteristic strength (Fc') is the cheapest alternative not just to reduce column size due to other disciplines requirements, but also to carry out a better design from value engineering point view (HSC) alternatives is cheaper that the original design). Also, it could be noted the using stronger concrete produces cheaper column, but this relation has practical limits depends on the relation between the column and the rest of building. For example, as per ACI-318, the strength of column's concrete should not be more than 1.4 times the strength of floor's concrete otherwise certain provision should be considered.
2) The second cheapest alternative is composite column, it will never be cheaper than the original traditional design, and hence, it is not an option for value engineering.
3) Its direct cost increases with increasing the steel percent that is why enclosed composite columns are favorable in case of low reduction percent of column size, where column size is relatively big and steel section could be embedded easily. Also, this alternative allows the designer to use the required area of steel section without any waste unlike the in-filled composite column.
4) In-filled composite is not favorable in low reduction percent of column size because the minimum tube thickness depends on column size, which is relatively big in this case. The minimum tube thickness to prevent local buckling causes additional unnecessary steel percent and leads to more expansive column. On other hand, in case of high reduction percent of column size, the tube thickness is fully effective which makes its efficiency as same as the enclosed one.
5) The more required size reduction percent, the smaller column size. At certain level of reduction, column size will be too small for steel core to be embedded, at this point; in-filled composite column will be the suitable alternative.
6) The more size reduction percent the less concrete contribution in in-filled column behavior, at certain level of size reduction the concrete part effect could be neglected and steel section dominate the column behavior. At this point pure steel column will be the only available alternative.

From stiffness point of view the optimum alternative could be selected based on the following analysis:

1) Reducing concrete column size decreases its axial stiffness even with increase (Fc') because the elastic modulus of concrete (Ec) proportions with ($\sqrt{Fc'}$).
2) Due to neglecting concrete tensile strength in design, the flexural stiffness of concrete column depends only on its size and re-bars percent.
3) Since (Es) is constant, stiffness of steel column depends only its section properties, hence, its axial stiffness is independent from size unlike its flexural one.
4) Because of creep effect, only one fifth of concrete elastic modulus is considered in the equivalent elastic modulus of composite columns. This is why both axial and flexural stiffness of composite columns (enclosed or in-filled) depended mainly on their steel section. Also, because steel core of enclosed composite column is always compacted to fit in the concrete, it has a relatively small moment of inertia and accordingly small flexural stiffness. Oppositely, the large tubular steel section of in-filled composite column has higher moment of inertia and accordingly better flexural stiffness.
5) Referring to results in table (3), although axial stiffness of HSC alternatives are less than the original design, but they still better than those of composite and steel columns. Accordingly, when column shortening is significant issue (as in high rise buildings) it is recommended to use HSC alternative.

6) Also table (3) shows that flexural stiffness of all alternatives are strongly affected be size reduction, hence, they are expected to suffer excessive drift under lateral loads unless they are braced to huge stiffness such as cores or shear walls.
7) Ultimate moment resistance of all alternatives also strongly affected by column size reduction, at high axial stresses (P=90%Pu), HSC columns have advantage on other alternatives, while at low axial stresses (P=50%Pu) all alternatives are almost equivalents. Accordingly, HSC column is preferred for braced high raise buildings.

From constructability point of view which presented in this research by number of required construction activities, the following could be noted:

1) Both concrete and steel columns need three construction activities, while enclosed composite column needs four construction activities and in-filled composite column needs five construction activities.
2) Most design codes put restrictions on the percent of load that transfer from floor to steel section of composite columns by bond and demand special connection between composite column and floor, which add more complication and activates to this alternative.
3) Another contractual difficulty may accrue due to conflicts and mis-coordination and leakage of liability between different sub-contractors.
4) Because steel column doesn’t need curing and could be loaded immediately after erection, it is the fastest alternative.

5. CONCLUSIONS

Previous analysis of study results could be concluded as follows:

1) Using higher compressive strength concrete is the optimum alternative not only to reduce column size but also to carry out better design from value engineering point of view. This conclusion is valid up to the allowable limits specified in design codes such as the maximum ratio between concrete strengths of columns and floors and the maximum percent of reinforced steel. According to ACI-318, (Fc’ col / Fc’ floor) should not exceed 1.4 and maximum percent of reinforced steel is (4% to 6 %) according to column location from slab edge.
2) Beyond the limits of the HSC column, the optimum alternative from cost and behavior point of view is enclosed composite column which is valid as long as the required steel section is small enough to fit in to the concrete column.
3) Beyond the limits of the enclosed composite column, the optimum alternative from cost and behavior point of view is in-filled composite column which is valid as long as the steel section contribution is less that 90% of the total capacity of the column, this is equivalent to (As/Ac) ≈ 25%.
4) Beyond the limits of the in-filled composite column, high strength steel column the only available alternative.
5) Although composite column (enclosed or in-filled) may be optimum from cost and behavior point of view, but it may be not preferred practically due to its construction and contractual complications, which make steel column more acceptable alternative.
6) Although steel column is the most expansive alternative, but it is also the fastest one, hence, it is the favorable choice for tight time frame projects
7) This study is based on the average rates in USA and Canada, results may be slightly changed for other countries and different rates.
8) Reduction of column size effects on floor design such as punching stresses and relative stiffness between columns and beams are not considered in this research.

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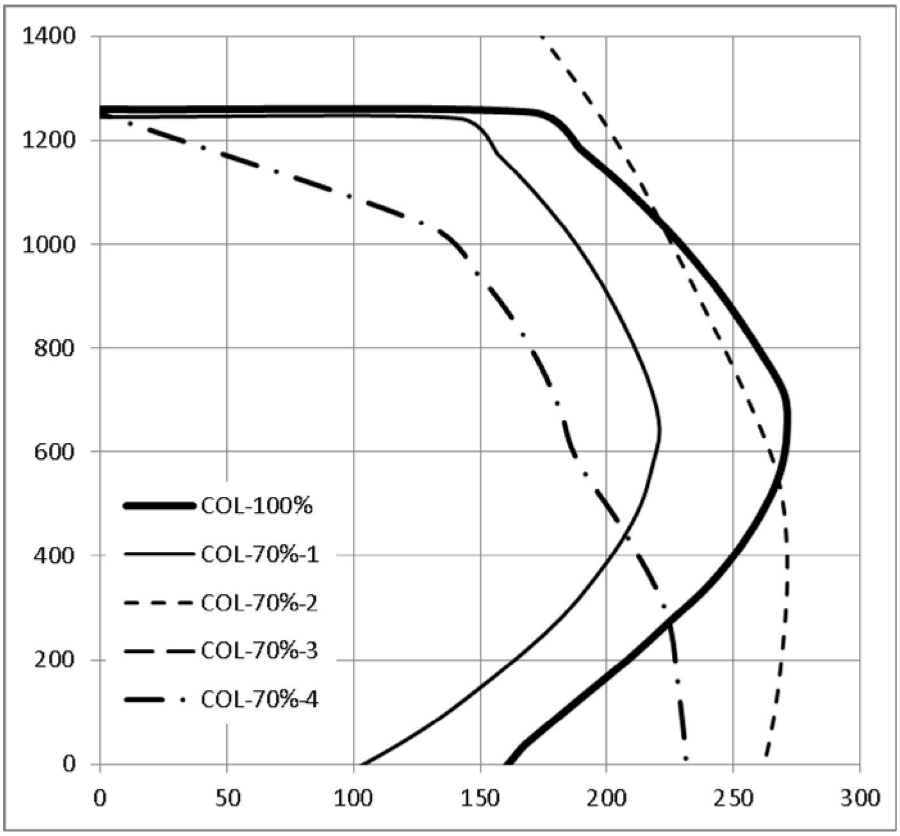

Figure (1): Interaction diagrams for group (1) columns (Column size Reduced to 70%)

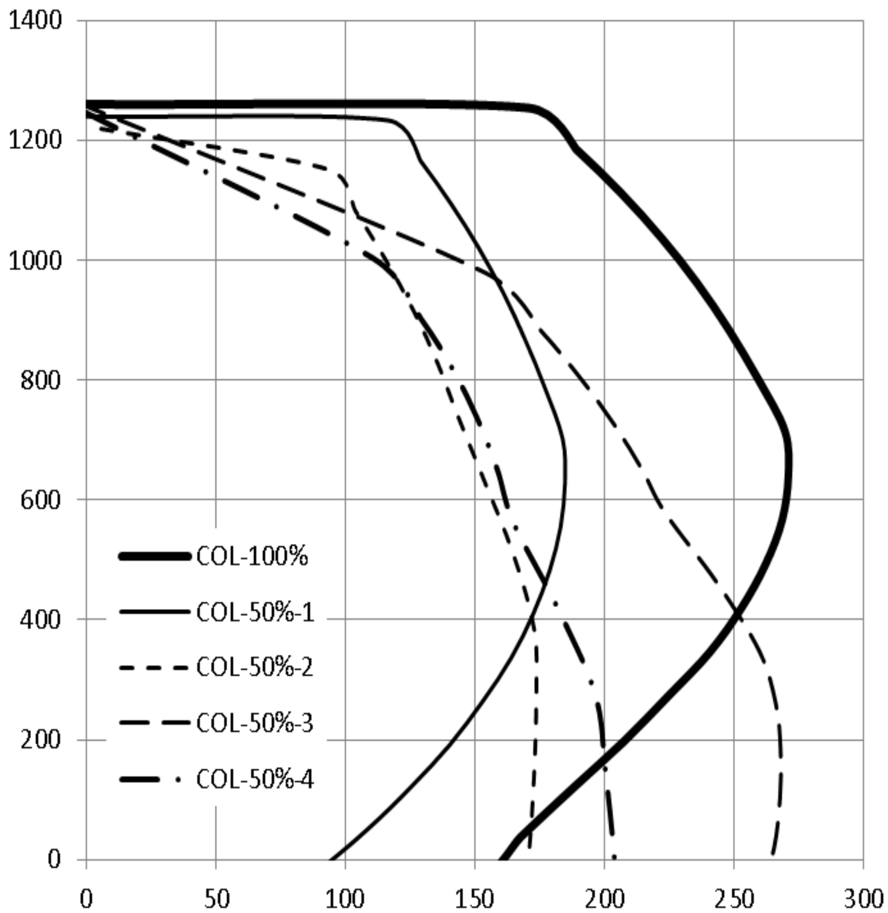

Figure (2): Interaction diagrams for group (2) columns (Column size Reduced to 50%)

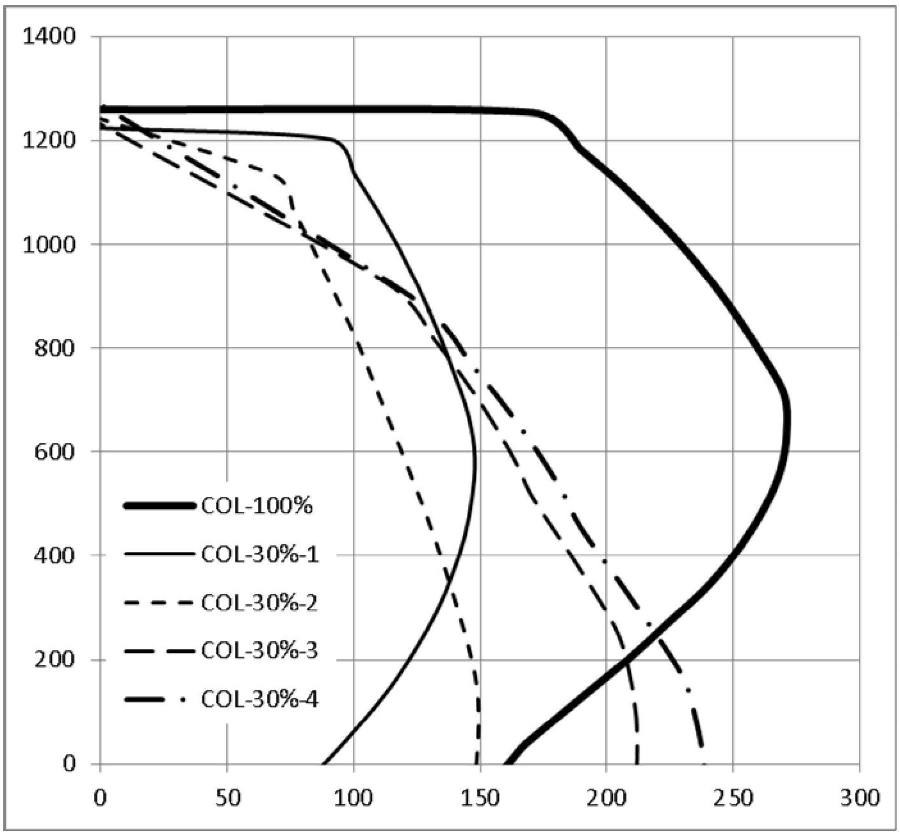

Figure (3): Interaction diagrams for group (3) columns (Column size Reduced to 30%)

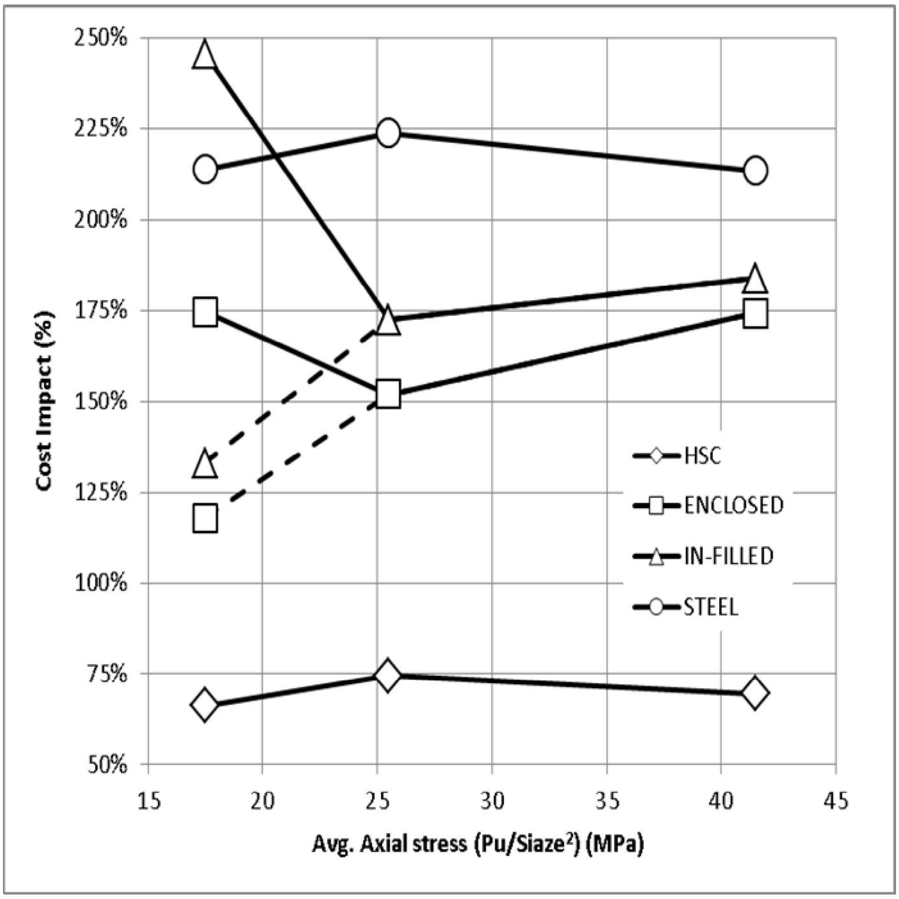

Figure (4): Relation between direct cost and average axial stress for all alternatives

Table (1): Graphical presentation for parametric study

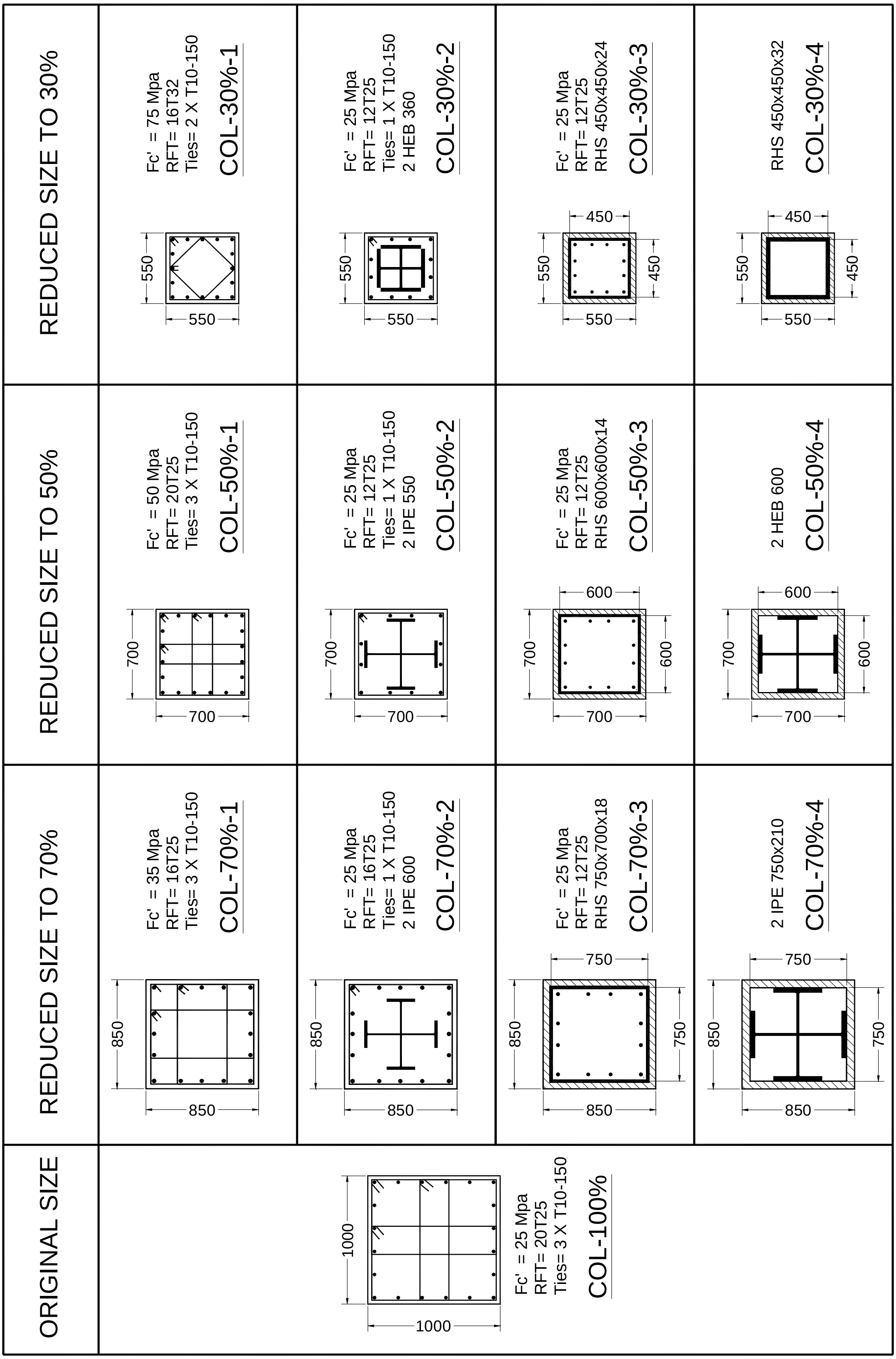

Table (2): Summary for data used in parametric study

ITEM	Unit	Original COL-100%	Reduced to 70% COL-70%-1	COL-70%-2	COL-70%-3	COL-70%-4	Reduced to 50% COL-50%-1	COL-50%-2	COL-50%-3	COL-50%-4	Reduced to 30% COL-30%-1	COL-30%-2	COL-30%-3	COL-30%-4
Alternatives														
System		NSC	HSC	Enclosed	In-filled	Steel	HSC	Enclosed	In-filled	Steel	HSC	Enclosed	In-filled	Steel
Fc'	kg/cm2	250	350	250	250	-	500	250	250	-	750	250	250	-
Dim.	cmxcm	100x100	85x85	85x85	75x75	75x75	70x70	70x70	60x60	60x60	55x55	55x55	45x45	45x45
RFT		20T25	16T25	16T25	12T25	-	20T25	12T25	12T25	-	16T32	12T25	8T25	-
Ties		3xT10-150	3xT10-150	T10-150	-	-	3xT10-150	T10-150	-	-	2xT10-150	T10-150	-	-
Steel Section		-	-	2 IPE 600	Box 18mm	2 IPE 750x210	-	2 IPE 550	Box 14mm	2 HEB 600	-	2 HEB 360	Box 24mm	Box 32mm
Section Prop.														
Ac	cm2	10000	7225	7225	5625	0	4900	4900	3249	0	3025	3025	1600	0
Ic	cm4	8333333	4350052	4350052	2636719	0	2000833	2000833	879667	0	762552	762552	213333	0
Ec	t/m2	2.50E+06	2.50E+06	5.00E+05	5.00E+05	0	3.50E+06	5.00E+05	5.00E+05	0	4.30E+06	5.00E+05	5.00E+05	0
Ar	cm2	98	78.4	78.4	58.8	0	98	58.8	58.8	0	128	58.8	39.2	0
As	cm2	0	0	312	527	536	0	269	328	547	0	361	408	535
Is	cm4	0	0	95500	471000	271000	0	69700	188000	187500	0	53200	124000	157000
Es	t/m2	0	0	2.00E+07	2.00E+07	2.00E+07	0	2.00E+07	2.00E+07	2.00E+07	0	2.00E+07	2.00E+07	2.00E+07
Ar/Ac	%	0.98%	1.09%	1.09%	1.05%	-	2.00%	1.20%	1.81%	-	4.23%	1.94%	2.45%	-
As/Ac	%	0.00%	0.00%	4.32%	9.37%	-	0.00%	5.49%	10.10%	-	0.00%	11.93%	25.50%	-
Material Rates														
Ready-mix Conc.	$/m3	175.0	195.0	175.0	200.0	0.0	220.0	175.0	200.0	0.0	275.0	175.0	200.0	0.0
Re-bars	$/kg	1.5	1.5	1.5	1.5	0.0	1.5	1.5	1.5	0.0	1.5	1.5	1.5	0.0
Ties	$/kg	1.7	1.7	1.7	0.0	0.0	1.7	1.7	0.0	0.0	1.7	1.7	0.0	0.0
Formwork	$/m2	13.6	13.6	13.6	0.0	0.0	13.6	13.6	0.0	0.0	13.6	13.6	0.0	0.0
Steel Sec.	$/kg	0.0	0.0	2.5	2.5	2.5	0.0	2.5	2.5	2.5	0.0	2.5	2.5	2.5
Anti-rust coat	$/m2	0.0	0.0	0.0	7.3	7.3	0.0	0.0	7.3	7.3	0.0	0.0	7.3	7.3
Fire Protection	$/m2	0.0	0.0	0.0	33.9	33.9	0.0	0.0	33.9	33.9	0.0	0.0	33.9	33.9
Labor & Equib. Rates														
Formwork	$/m2	33.9	33.9	33.9	0.0	0.0	33.9	33.9	0.0	0.0	33.9	33.9	0.0	0.0
Re-bars	$/kg	0.8	0.8	0.8	0.8	0.0	0.8	0.8	0.8	0.0	0.8	0.8	0.8	0.0
Casting	$/m3	21.5	21.5	21.5	21.5	0.0	21.5	21.5	21.5	0.0	21.5	21.5	21.5	0.0
Steel Erection	$/kg	0.0	0.0	0.5	0.5	0.5	0.0	0.5	0.5	0.5	0.0	0.5	0.5	0.5
Anti-rust coat	$/m2	0.0	0.0	0.0	4.0	4.0	0.0	0.0	4.0	4.0	0.0	0.0	4.0	4.0
Fire Protection	$/m2	0.0	0.0	0.0	18.1	18.1	0.0	0.0	18.1	18.1	0.0	0.0	18.1	18.1

Table (3): Summary for parametric study results

ITEM	Unit	Original COL-100%	Reduced to 70% COL-70%-1	COL-70%-2	COL-70%-3	COL-70%-4	Reduced to 50% COL-50%-1	COL-50%-2	COL-50%-3	COL-50%-4	Reduced to 30% COL-30%-1	COL-30%-2	COL-30%-3	COL-30%-4
Capacity														
Pu	ton	1260	1260	1630	1920	1250	1240	1225	1255	1245	1260	1240	1230	1270
Mu90, P=90%Pu	m.ton	206	165	168	145	70	130	95	75	55	100	70	60	50
Mu50, P=50%Pu	m.ton	270	260	245	445	185	185	155	220	160	145	120	160	175
Mu90/Mu50		76%	63%	69%	33%	38%	70%	61%	34%	34%	69%	58%	38%	29%
Mu90 Impact		100%	80%	82%	70%	34%	63%	46%	36%	27%	49%	34%	29%	24%
Mu50 Impact		100%	96%	91%	165%	69%	69%	57%	81%	59%	54%	44%	59%	65%
Stiffness														
EA	ton	2.50E+06	1.81E+06	1.14E+06	1.45E+06	1.07E+06	1.72E+06	9.01E+05	9.36E+05	1.09E+06	1.30E+06	9.91E+05	9.74E+05	1.07E+06
EI	ton.m2	2.08E+05	1.09E+05	4.09E+04	1.07E+05	5.42E+04	7.00E+04	2.39E+04	4.20E+04	3.75E+04	3.28E+04	1.45E+04	2.59E+04	3.14E+04
Axial Stiffness. Impact		100%	72%	46%	58%	43%	69%	36%	37%	44%	52%	40%	39%	43%
Flexural stiffness Impact		100%	52%	20%	52%	26%	34%	11%	20%	18%	16%	7%	12%	15%
Quantities														
RC Vol	m3/m	1.00	0.72	0.72	0.56	0.00	0.49	0.49	0.32	0	0.30	0.30	0.16	0.00
RFT	kg/m	77	62	62	46	0	77	46	46	0	100	46	31	0
Ties	kg/m	37	13	8	0	0	25	11	0	0	13	8	0	0
Formwork	m2/m	4	2.2	2.2	0	0	2.8	2.8	0	0	2.2	2.2	0	0
Steel Sec.	kg/m	0	0	245	414	421	0	211	257	429	0	283	320	420
Anti-rust coat	m2/m	0	0	0	1.8	1.8	0	0	2.8	2.5	0	0	1.8	1.8
Fire Protection	m2/m	0	0	0	2.2	2.2	0	0	2.8	2.8	0	0	2.2	2.2
Activities														
Formwork		1	1	1	0	0	1	1	0	0	1	1	0	0
RFT		1	1	1	1	0	1	1	1	0	1	1	1	0
Casting		1	1	1	1	0	1	1	1	0	1	1	1	0
Steel Erection		0	0	1	1	1	0	1	1	1	0	1	1	1
Anti-rust coat		0	0	0	1	1	0	0	1	1	0	0	1	1
Fire Protection		0	0	0	1	1	0	0	1	1	0	0	1	1
Direct Cost														
Material	$/m	405	283	869	1297	1134	301	734	888	1181	283	869	961	1132
Labor & Equib.	$/m	247	149	270	306	261	186	258	236	279	171	268	238	260
Direct Cost	$/m	653	432	1139	1602	1395	487	992	1124	1460	454	1137	1199	1392
Cost impact		100%	66%	175%	246%	214%	75%	152%	172%	224%	69%	174%	184%	213%