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Strength and behaviour assessment of axially loaded concrete filled steel tubular stub columns

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Stub columns
CFST
3D Analysis
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ABSTRACT

As a result of the excellent performance under different loading conditions, concrete-filled steel tubular (CFST) stub columns are extensively used recently. The current study employs a 3D finite element analysis to assess the response of (CFST) stub columns when subjected to axial compression. The effect of some parameters of concrete and the confining steel tube where numerically investigated. The steel was considered as an elastic perfectly plastic material, whereas a damage plasticity behaviour was adopted for the concrete material. Analysis results suggested that the ultimate strength of concrete increases with the increase of its grade. On the other hand, increasing magnitudes of concrete grade caused a reduction in the ductility of the composite columns. Also, the increase in the steel yields stress, and the steel tube wall thickness contributes to an increase in the columns' ultimate strength. However, they reduce the action of the concrete grade that increases the column's ultimate strength. It was also noted that the ductility that the circular CFST stub columns showed is larger than that for square columns. Thus, the use of square CFST columns with high strength concrete, especially in seismically active areas, should be carefully considered.

1. INTRODUCTION

The structural advantages and superior response of the concrete filled steel tubular (CFST) columns qualifies them as one of the essential elements in modern structural construction. The interaction of their components contributes to the resistance of applied loads. The confinement pressure of the steel tube makes the concrete core behaves like a material with a triaxial stress state. Meanwhile, the concrete core itself plays a role in eliminating or mitigating the local buckling that may occur in the steel tube. This interaction behaviour means that CFST columns have demonstrated greater strength against axial compression, a higher energy absorption capacity, a better ductility performance, and lower strength degradation than steel hollow sections and reinforced concrete columns if they used separately. Researchers have experimentally and analytically studied the response of of CFST columns under different loading conditions. These studies have provided an extensive database for several design codes in order to develop their design approaches and practices for composite columns, such as those specified in the Eurocode 4, AISC specification, and ACI code. Due to its ability in simulating different structural element, Finite Element Analysis (FEA) can be considered as an effective tool in modelling the CFST columns. However, the accuracy of the FEA is more impacted by the selection of the material modelling for both steel and concrete compared with the other input parameters (Mallesh et al. 2016). Therefore, different material models were developed in previous studies to improve the prediction accuracy of the FEA. Han et al. (2007) suggested a procedure for the numerical modelling of CFST columns subjected to pure torsion. The analysis was conducted by modelling the concrete material as a damaged plasticity model. An elastic perfect plastic model was adopted to define the response of steel material. They developed formulae to predict the ultimate torsional capacity of such composite columns. Deng et al. (2013) theoretically and numerically investigated the flexural behaviour of CFST composite members using FEA. ANSYS software was adopted for a finite element modelling of the problem. Both theoretical and numerical approaches were validated against published experimental studies. They showed that both analysis procedures have the ability to predict the behavioural stages of CFST members, with more accurate results showed by

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theoretical analysis. Yang et al. (2013) developed a finite element model to simulate ultra-high strength concrete-filled steel tubes under compression using ABAQUS software. They validated their model by comparing the simulation results with the data of some experimental tests. Bagherinejad et al. (2015) numerically studied the effect of eccentric loading on the buckling behaviour of rectangular CFST columns using ABAQUS software. Zhao et al. (2018) used experimental and numerical analyses to investigate the behavior of large-scale circular CFST columns under axial compression. They concluded that the horizontal stiffener has a significant constraining effect on the external deformation at the surface of steel tube, whereas the vertical stiffeners may improve the bending resistance and initial stiffness of the column. Al-Kutti (2018) investigated the possibility of using the Drucker Prager model in the simulation of concrete material for the finite element modelling of concrete CFST members. He suggested empirical formulae to evaluate the material model parameters for confined concrete under compression with a compressive strength that ranged from 25 to 100 MPa. Also, in 2018, Ouyang and Kwan (2018) developed a numerical model to study the performance of square CFST columns taking into account the triaxial behaviour and lateral expansion of the concrete core. They found that the increase of corner radius of steel sections improves the post-peak response of columns with square sections. Nguyen et al. (2019) employed a nonlinear finite element analysis to study the effect of tie and slip models in the representation of steel concrete interaction on the flexural resistance of the compact CFST columns. The comparison with some experimental data showed that the tie model provided higher accurate results compared with those predicted by the slip model.

It can be noted from the previous literature review that the interaction in the behaviour of the steel and concrete materials and the configuration of CFST column section may represent the major factors that must be considered in more details with the analysis of such members. However, most of the previous research studied the effect of some parameters in the analysis of CFST columns without considering the variation of other parameters that may lead to significant changes in the strength and behaviour of such structural members. In the present work, a three-dimensional, nonlinear FEA was conducted using ABAQUS software to assess the strength and behaviour of CFST stub columns under axial compression. The effects of the concrete strength (grade of concrete), the steel yield stress, the steel tube wall thickness, and the section shape (circular and square) were examined. This assessment may help to understand the parameters that could play a major role in the axial compressive strength of such composite columns.

2. FINITE ELEMENT MODELLING AND VERIFICATION

2.1. General

In the current study, ABAQUS software has been employed in the finite element analysis. Eight-noded brick elements (C3D8R) were employed to simulate the structural elements (concrete and steel tube) of the CFST columns. To determine an optimal finite element mesh that gives a low computational time with a relatively accurate solution, mesh convergence studies were investigated. The element size was chosen as 5% of the overall diameter (circle) or width (square) for column cross-sections. The adopted finite element mesh for both shapes of CFST columns is presented in Fig. 1.

The concept of surface-to-surface contact, presented by Tao et al. (2011), has been used to simulate the interaction between the concrete and steel. As per this method, a coefficient of friction of 0.6 in a direction tangent to the interaction face was adopted in the Coulomb friction model. In addition, a hard contact model was used in the normal direction between the two contact surfaces of steel and concrete. This can prevents the penetration of the interface in compression and permits its separation in tension. According to Tao et al. (2013), the initial local imperfections have no important influence on the response of CFST columns. Therefore, it has been ignored in the modelling procedure.

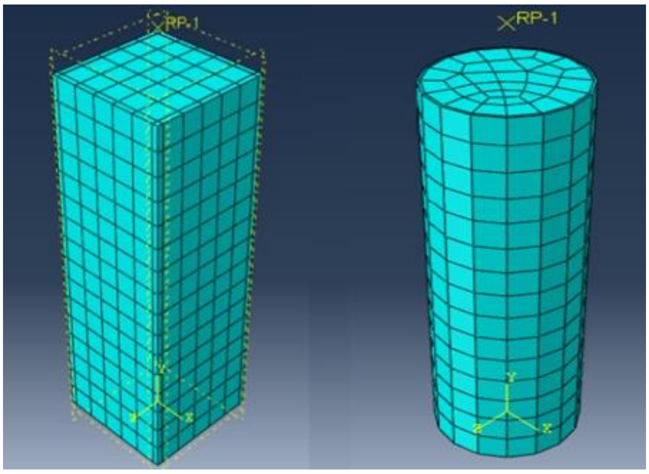

Figure 1. Finite element mesh for the CFST columns used in the analysis

2.2. Material Modelling

In the present study, the constitutive behaviour of the steel was considered as an elastic perfectly plastic material, with a modulus of elasticity equals to 200 GPa and a Poisson's ratio of 0.3. Moreover, Von-Mises yield criterion was used to define the steel material yield surface. The damage plasticity model was adopted to model the concrete material.

As the CFST columns loaded axially, the concrete core expanded laterally and confined by the outside steel tube. Due to this confinement, an increase in the strength and ductility of the concrete could be induced. The constitutive stress strain relationship for the concrete and corresponding parameters of the damage plasticity model were considered as suggested by Tao et al. (2013). Moreover, Poisson's ratio was taken as 0.2, and the value of initial modulus of elasticity was calculated as $4700\sqrt{f_c'}$, as recommended by ACI Committee 318.

2.3. Boundary Conditions and Loading

Most researchers used end plates when testing the CFST stub columns in order to minimize any influences on the end conditions. Therefore, it is suitable to use clamped end conditions for the top and bottom surfaces of the structural member, in which all degrees of freedom will be fixed except the top axial displacement where the load is applied. On the other hand, a displacement control mode was considered to simulate the applied axial compression at the top end of the modelled CFST stub columns.

2.4. Model Verification

In order to check the accuracy and efficiency of the adopted procedure, the predicted behaviour and ultimate compressive strengths were compared with some previous experimental data. The adopted experimental tests specimens were chosen with various dimensions and material properties to cover a wide range of case studies, which have been investigated by different researchers. The dimensions, material properties and values of the predicted ultimate compressive strength (N_{up}) and the experimental test strength (N_{ue}) of the selected specimens for verification are given in Tables 1 and 2. It can be observed that the predicted outputs showed a good agreement with the test results, where mean values of 1.008 and 1.035 for the ratio (N_{ue}/N_{up}) were obtained with standard deviation values of 0.071 and 0.036 for specimens with square and circular cross-sections, respectively. Moreover, Fig. 2 and 3 show a comparison between the numerically predicted and experimentally measured axial load – axial shortening profiles for the analysed members.

3. RESULTS AND DISCUSSION

The verified nonlinear finite element model was used to carry out a parametric study aims to assess the performance of stub columns under different conditions. A total of eighty columns, equally divided into two categories (i.e. square and circular sections), were analyzed under axial compression. The concrete grade (f_c'), the steel yield stress (f_y), the steel tube wall thickness (t), and the section shape (circular and square) were considered the main parameters. All columns were chosen with the same diameter or width (D) (at 125 mm) and with two values of (D/t) ratios (namely 50 and 25). To avoid impacting the end conditions and overall buckling, the length of the analyzed stub columns (L) was chosen as 3D. A summary of the CFST stub columns' details is presented in Tables 3 and 4, whereas the resulting axial load versus the axial shortening relationships are shown in Figs. 4 and 5.

3.1 Strength Assessment

The strength and behaviour of concrete core are largely affected by its grade value. Therefore, five grades of concrete, ranging from 25 to 85 MPa, were considered to cover the behaviour of such structural members with normal and high strength concretes. It can be seen from Table 3 that the ultimate capacity of columns increases as the concrete compressive strength increases. However, the action of this parameter may be reduced with the variation in other parameters. It was noted that, when the concrete grade increased from 25 to 85 MPa for a circular CSFT column, where a D/t ratio of 50 and a steel yield stress of 275 MPa, a double value of the column's ultimate capacity has been obtained. Moreover, for a column with the same properties, excepting the steel yield stress of 500 MPa, the ultimate strength was increased by about 72%. On the other hand, the increase in ultimate strength along with the increase in concrete grade reduced by 20% when the D/t ratio changed from 50 to 25.

Four values of steel yield stresses of 275, 350, 425, and 500 MPa were examined to assess their influence on the ultimate capacity of the considered CFST columns. It was noted that the ultimate capacity of the circular columns with a D/t ratio of 50 and a concrete grade of 25 MPa increased by about 42% when the value of steel yield stress increased from 275 to 500 MPa. However, the increasing percentage was only 20% when the concrete grade value is 85 MPa. Whereas, with the change of (D/t) ratio from 50 to 25 and the same concrete grade of 25 MPa is adopted, the ultimate capacity of the analyzed circular columns increased by 46% and 57% with steel yield stress values of 275 MPa and 500 MPa, respectively. The variation in the columns' strengths with respect to the considered parameters is presented in Table 4 for those CFST columns with square sections. It can be noticed that the effect of each individual parameter is slightly more in the square than that in the circular columns.

To consider the influence of the shape of CFST column cross section on its ultimate capacity, a strength index is adopted to verify the column section strength as $SI = N_{up}/N_{uo}$, where $N_{uo} = A_s f_y + 0.85 A_c f_c'$, as determined by the ACI code for the evaluation of sectional capacity of such composite columns, A_s and A_c are the cross sectional areas of steel and concrete, respectively.

The strength index (SI) is calculated for each individual column, and the results are shown in Tables 3 and 4. Numerical results showed, in general, that SI values for columns with circular section is considerably greater than that for the columns with square sections. In addition, the strength index decreased with the increased concrete grade for circular columns, but increased for square columns. This may be related to the interaction between the concrete core and the surrounding steel tube, which is more efficient in circular columns than in square columns. On the other hand, there is no significant change in the effect of the column shape on the strength index with the change of steel yield stress or steel tube thickness.

3.2 Behaviour Assessment

As can be seen in Figs. 4 and 5, the axial load versus the axial shortening relationships were generally similar in shape until the ultimate load is reached. After that, a difference can be noticed due to the effect of the considered parameters. Nevertheless, in spite of the increase in the steel yield stress, the ductility of the CFST columns reduced with the increase in concrete grade. This is agreed with the engineering expectation since the ductility of concrete reduces with the increase in its strength. On the other hand, it can be clearly noted that the reduction in the values of D/t ratio caused an increase in the ductility of the stub columns. This is mainly due to the increased in concrete confinement provided by the steel tube.

By comparing Figs. 4 and 5, it can be observed that circular columns are more ductile than the square, where the post peak curves of square columns are steeper than those obtained in the circular columns. This may be attributed to the property of the circular shape for the steel tube, which could produce more efficient confinement and then more ductile behaviour to the concrete core than the square steel tubes.

4. CONCLUSIONS

The study adopted a three-dimensional, nonlinear finite element analysis using ABAQUS software to assess the response of CFST stub columns subjected to axial compression. The influence of a number of parameters that could affect the performance of this kind of structural members were investigated. These parameters include the grade of concrete, the steel yield stress, the steel tube wall thickness, and the shape of the column cross-section (circular or square). A total of eighty stub columns divided into two groups depending on their cross-sectional shape were analyzed. Based on the results of the parametric study, a number of conclusions can be drawn:

1. The increase of concrete grade leads to an increase in the ultimate strength of CFST stub columns. On the other hand, a reduction in the ductility has been observed when concrete grade increased.
2. The changes in steel yield stress and D/t ratio have caused a significant influence on the ultimate strength and ductility of columns, in which an increase in their values was observed. The effect of these two parameters may reduce with the increase in concrete grade.
3. The composite interaction of concrete in the presence of the surrounding steel tube plays an important role in determining the strength index, SI, values. The effect of this interaction is more pronounced when circular sections are adopted.
4. CFST columns with circular columns showed higher ductility than that obtained in the case of square section.
5. The ductility of circular CFST stub columns is higher than that of square CFST columns. Thus, the use of square CFST columns with high strength concretes should be carefully considered, especially inseismically active areas.

Table 1. Test data for Square CFST stub columns

No	Specimen Label	Dimensions (mm) D	t	L	f_c' (MPa)	f_y (MPa)	N_{up} (kN)	N_{ue} (kN)	N_{ue}/N_{up}	Test Source
1	A1	120	5.80	360	83.0	300.0	1744	1697	0.973	Liu and Gho (2005)
2	RC2-1	120	2.86	360	50.8	228.0	968	992	1.025	Han (2002)
3	UCFT25	250	2.50	750	50.1	234.3	3390	3230	0.953	Tao et al. (2005)
4	R7-1	106	4.00	320	89.0	495.0	1662	1749	1.052	Liu (2005)
5	SU-040	200	5.00	600	27.2	265.8	2043	2312	1.132	Huang et al. (2002)
6	NS1	186	3.00	540	32.0	300.0	1699	1555	0.915	Uy (2000)
Mean									1.008	
Standard Deviation									0.071	

Table 2. Test data for Circular CFST stub columns

No.	Specimen Label	Dimensions (mm) D	t	L	f_c' (MPa)	f_y (MPa)	N_{up} (kN)	N_{ue} (kN)	N_{ue}/N_{up}	Test Source
1	C4	115	3.99	300	83.9	343.0	1338	1308	0.978	Giakoumelis and Lam (2004)
2	C30-3	100	1.90	300	111.7	404.0	1050	1100	1.048	Yu et al. (2008)
3	D4M4C2	113	2.89	340	32.9	360.0	738	788	1.068	Gupta et al. (2007)
4	CU-040	200	5.00	600	27.2	265.8	1884	2013	1.068	Huang et al. (2002)
5	CC8-C-8	222	6.47	666	77.0	843.0	7237	7304	1.009	Sakino et al. (2004)
6	C1	140	3.00	602	28.2	285.0	849	881	1.038	Schneider (1998)
Mean									1.035	
Standard Deviation									0.036	

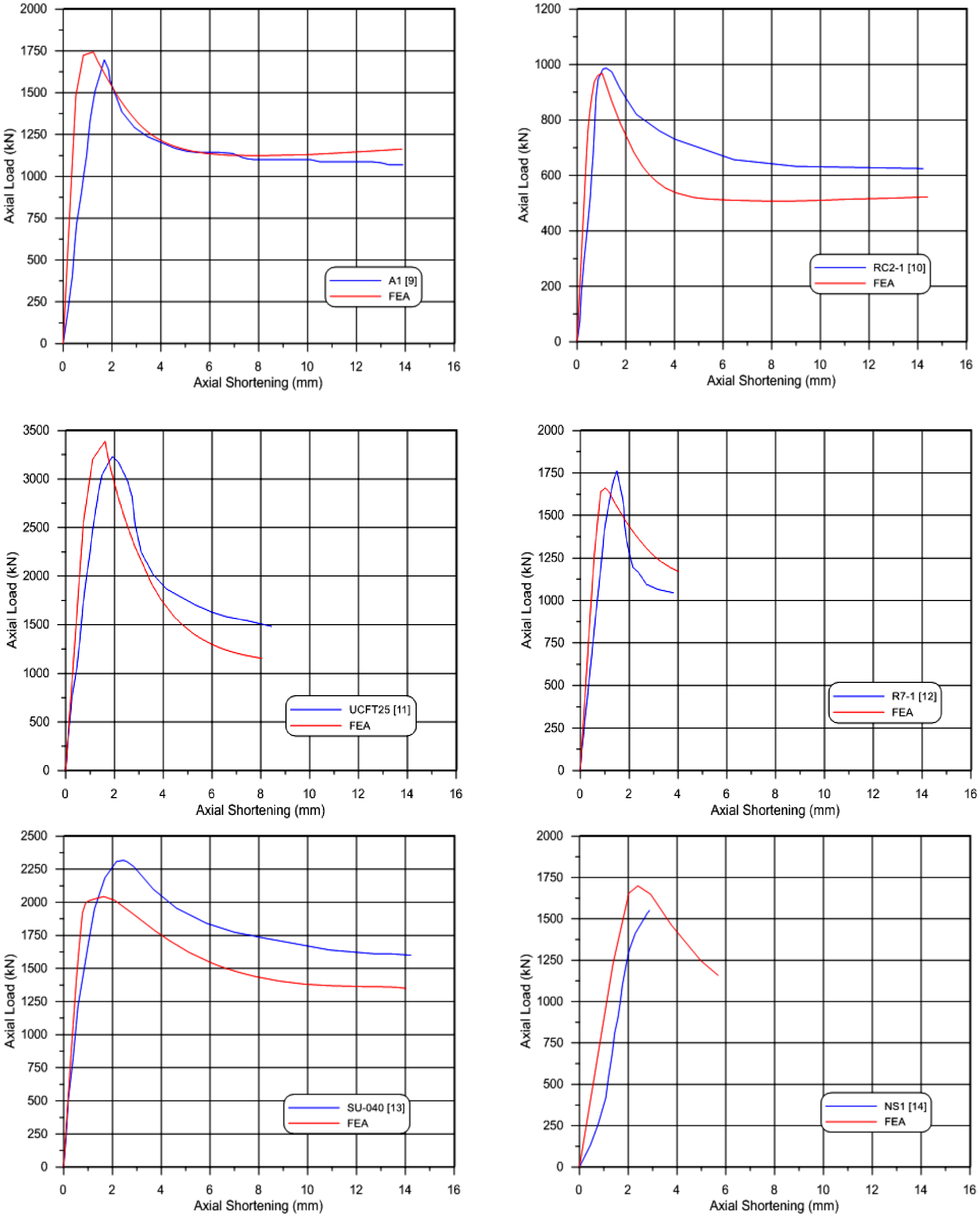

Figure 2. Predicted and measured axial load-axial shortening profiles for square CFST columns

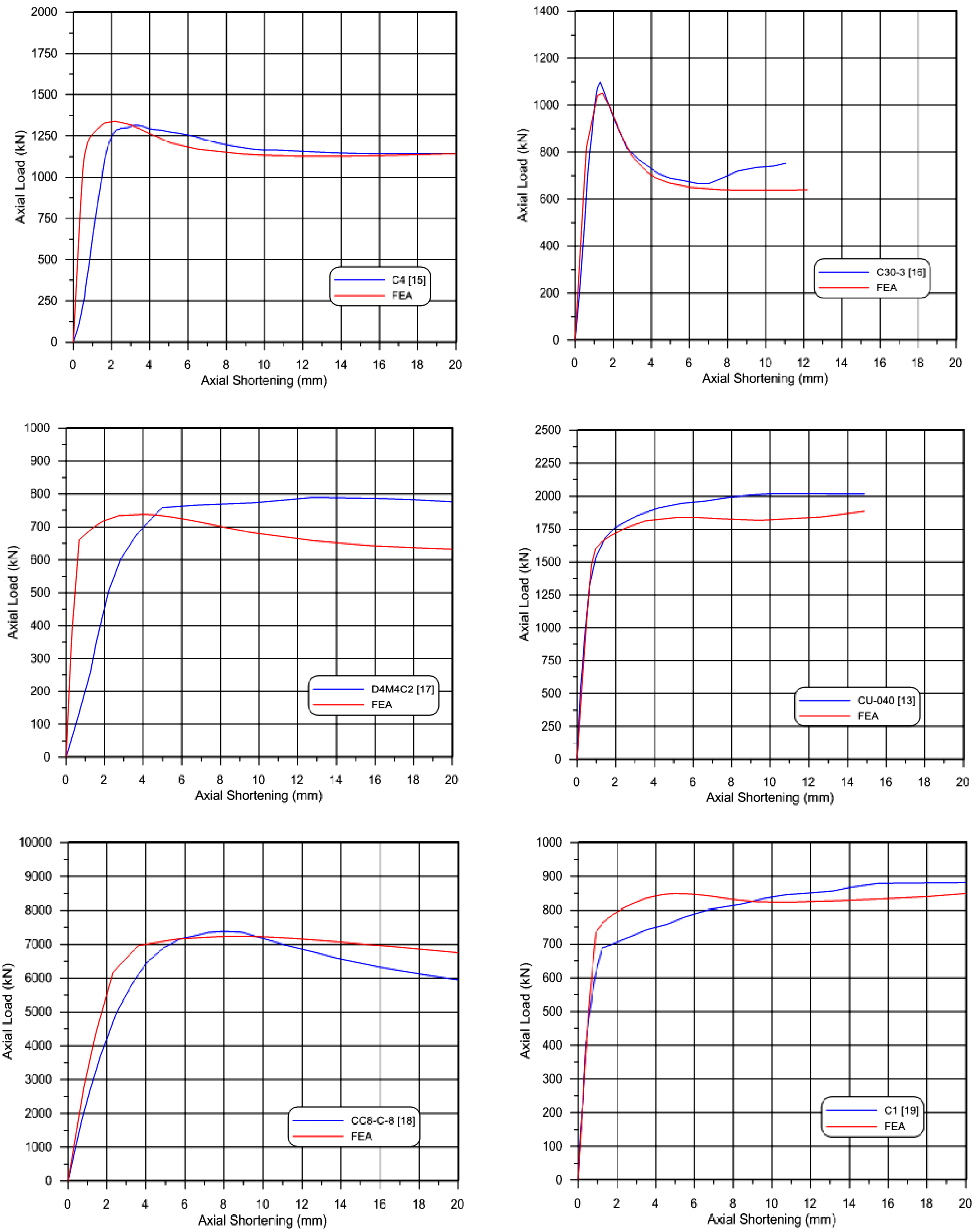

Figure 3. Predicted and measured axial load-axial shortening profiles for Circular CFST columns

Table 3. Details of analyzed circular CFST stub columns

No	D /t	f_y (MPa)	f_c' (MPa)	N_{up} (kN)	N_{uo} (kN)	SI
1	50	275	25	623	505	1.234
2			40	786	649	1.211
3			55	948	793	1.195
4			70	1105	938	1.178
5			85	1271	1082	1.175
6	50	350	25	713	577	1.235
7			40	876	721	1.215
8			55	1031	865	1.191
9			70	1205	1010	1.194
10			85	1371	1154	1.188
11	50	425	25	800	649	1.232
12			40	970	793	1.222
13			55	1118	938	1.192
14			70	1275	1082	1.179
15			85	1449	1226	1.182
16	50	500	25	887	721	1.229
17			40	1059	866	1.223
18			55	1221	1010	1.209
19			70	1368	1154	1.185
20			85	1523	1298	1.173
21	25	275	25	911	739	1.233
22			40	1072	872	1.230
23			55	1222	1004	1.217
24			70	1363	1136	1.199
25			85	1488	1269	1.173
26	25	350	25	1073	880	1.219
27			40	1237	1013	1.221
28			55	1393	1145	1.216
29			70	1538	1278	1.204
30			85	1671	1410	1.185
31	25	425	25	1235	1022	1.208
32			40	1404	1154	1.216
33			55	1565	1287	1.216
34			70	1709	1419	1.204
35			85	1850	1552	1.192
36	25	500	25	1391	1163	1.196
37			40	1568	1296	1.210
38			55	1729	1428	1.211
39			70	1877	1560	1.203
40			85	2024	1693	1.195

Table 4. Details of analyzed square CFST stub columns

No.	D /t	f_y (MPa)	f_c' (MPa)	N_{up} (kN)	N_{uo} (kN)	SI
1			25	705	643	1.097
2			40	912	826	1.104
3	50	275	55	1115	1010	1.104
4			70	1333	1194	1.117
5			85	1538	1377	1.117
6			25	804	735	1.095
7			40	1006	918	1.095
8	50	350	55	1211	1102	1.099
9			70	1433	1286	1.114
10			85	1635	1469	1.113
11			25	896	827	1.084
12			40	1100	1010	1.088
13	50	425	55	1320	1194	1.106
14			70	1526	1377	1.108
15			85	1731	1561	1.109
16			25	994	919	1.082
17			40	1204	1102	1.093
18	50	500	55	1414	1286	1.100
19			70	1627	1469	1.107
20			85	1836	1653	1.111
21			25	1008	941	1.071
22			40	1202	1110	1.083
23	25	275	55	1391	1278	1.088
24			70	1586	1447	1.096
25			85	1768	1616	1.094
26			25	1193	1121	1.064
27			40	1389	1290	1.077
28	25	350	55	1574	1458	1.079
29			70	1767	1627	1.086
30			85	1962	1796	1.093
31			25	1376	1301	1.057
32			40	1571	1470	1.069
33	25	425	55	1764	1638	1.076
34			70	1953	1807	1.081
35			85	2140	1976	1.083
36			25	1557	1481	1.051
37			40	1746	1650	1.058
38	25	500	55	1941	1818	1.068
39			70	2138	1987	1.076
40			85	2327	2156	1.079

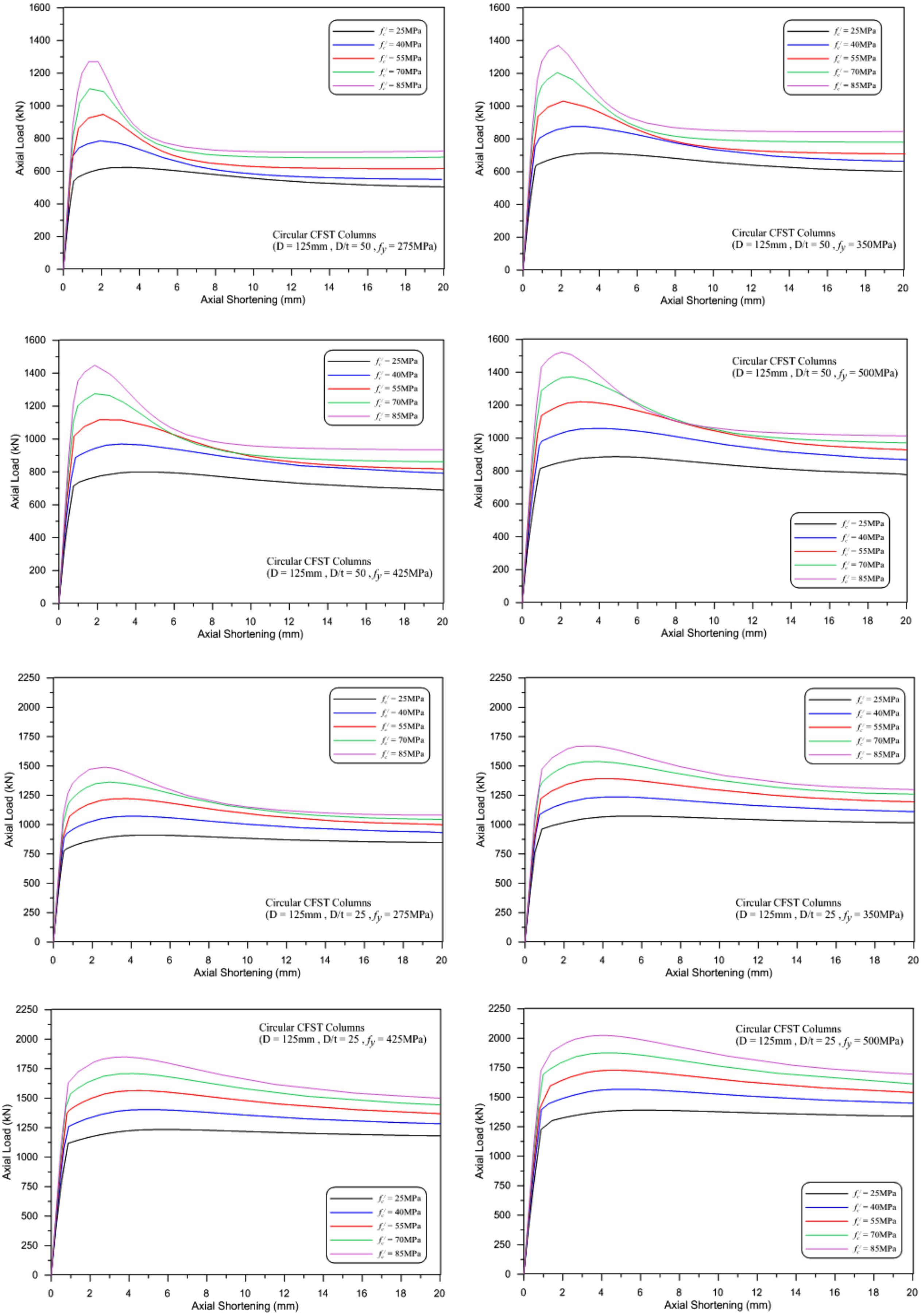

Figure 4. Axial load – axial shortening relationships for analyzed circular CFST Stub columns

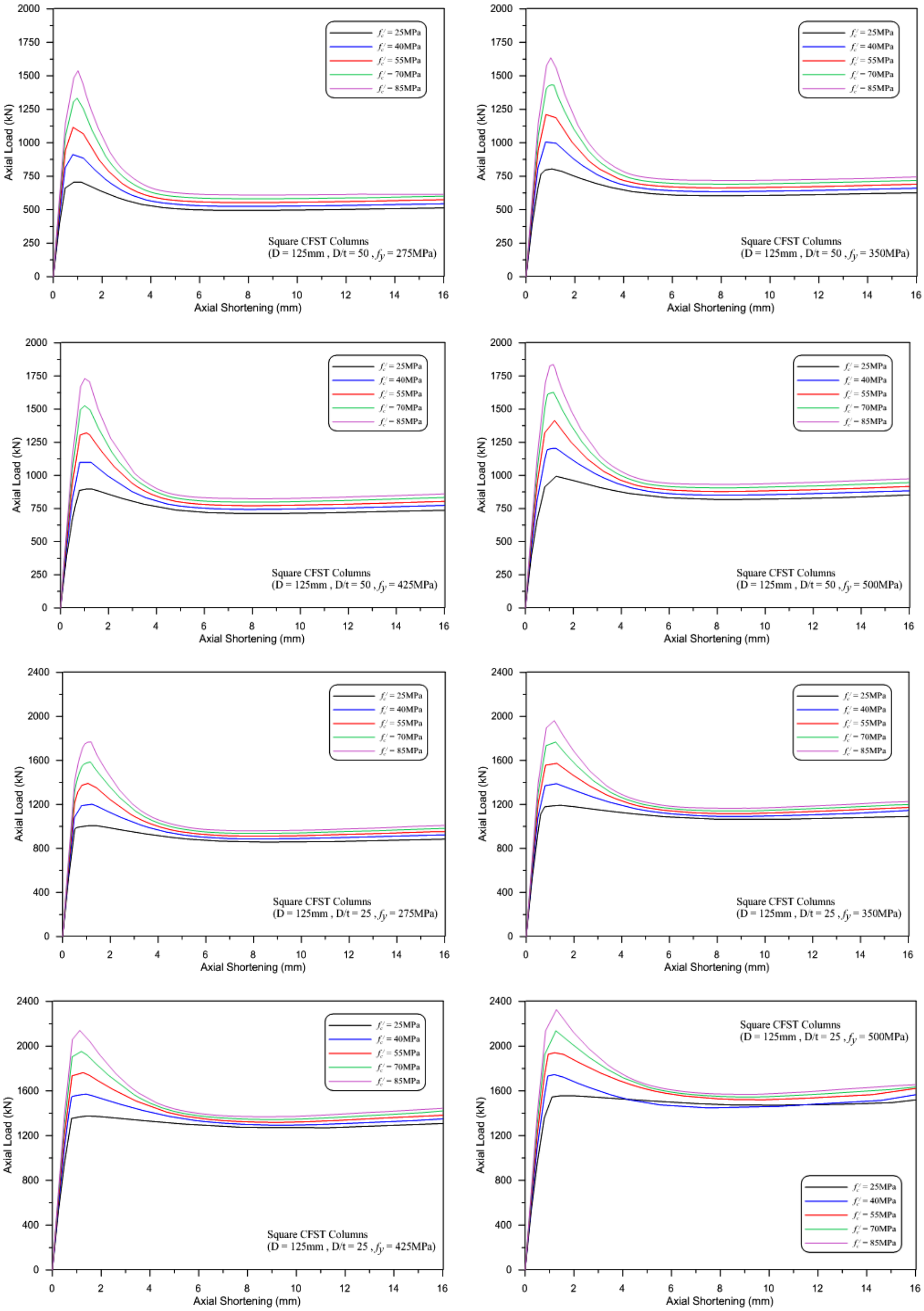

Figure 5. Axial load – axial shortening relationships for analyzed square CFST Stub columns

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