HARRAN ÜNİVERSİTESİ MÜHENDİSLİK DERGİSİ

HARRAN UNIVERSITY JOURNAL of ENGINEERING

e-ISSN: 2528-8733 (ONLINE)
URL: http://dergipark.gov.tr/humder

Comparison of the predictability of the ultimate axial strength of elliptical CFST columns using existing square and circular section-based code formulae

Mevcut kare ve dairesel kesit tabanlı kod formüllerini kullanarak eliptik BDÇT kolonlarının nihai eksenel dayanımının tahmin edilebilirliğinin karşılaştırılması

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Bu makaleye şu şekilde atıfta bulunabilirsiniz (To cite to this article): İpek S., Güneyisi E.M., "Comparison of the predictability of the ultimate axial strength of elliptical CFST columns using existing square and circular section-based code formulae", ***Harran Üniversitesi Mühendislik Dergisi***, 6(1): 12-27, (2021).

Erişim linki (To link to this article): http://dergipark.gov.tr/humder/archive

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Araştırma Makalesi

Comparison of the predictability of the ultimate axial strength of elliptical CFST columns using existing square and circular section-based code formulae

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Makale Bilgisi

Başvuru: 22/12/2021
Yayın: 30/04/2021

Keywords

Code formula
Concrete-filled steel tubular column
Elliptical section
Prediction
Ultimate axial strength

Anahtar Kelimeler

Kod formülü
Beton dolgulu çelik tüp
Eliptik kesit
Tahmin etme
Nihai eksenel dayanım

Abstract

The elliptical hollow section has been recently included in the family of the structural steel hollow sections. This type of steel section is also used in the production of concrete-filled steel tubular (CFST) members. For the elliptical CFST compression members, there is no specific design formulation in the current provisions, except the code called “Technical code for concrete-filled tubular structures” prepared by the Ministry of Housing and Urban-Rural Development of the People’s Republic of China. However, the formula proposed by this code for estimating the ultimate strength of the elliptical CFST columns was achieved by modifying the formula for predicting the ultimate strength of the square CFST members. In this context, the objective of this study is to evaluate the applicability of the existing code formulae that were proposed for the axially loaded CFST columns with rectangular or circular sections to that of columns with an elliptical section. To this, a data repository consisting of 97 experimentally tested elliptical CFST columns was compiled. Herein, the main criterion in the selection of the data was the axial loading condition. Thereafter, the prediction performance of these code formulae was assessed in terms of statistical parameters. The results indicated that the code formulae proposed for the circular-sectioned CFST columns have better prediction capability than that suggested for the rectangular sections. Among these design formulae proposed for the CFST columns with a circular section, the formulae recommended by the American Institute of Steel Construction, British Standard Institute, Canadian Standards Association, and Eurocode 4 performed the best prediction capability. These code formulae had the lowest mean absolute percent error values and R-squared values of higher than 0.8.

Mevcut kare ve dairesel kesit tabanlı kod formüllerini kullanarak eliptik BDÇT kolonlarının nihai eksenel dayanımının tahmin edilebilirliğinin karşılaştırılması

Öz

Eliptik içi boş profil, yapısal çelik içi boş profiller ailesine son zamanlarda dahil oldu. Bu tip çelik profil, beton dolgulu çelik tüp (BDÇT) elemanların üretiminde de kullanılmaktadır. Eliptik BDÇT basınç elemanları için muayyen bir tasarım formülü, Çin Halk Cumhuriyeti Konut ve Kentsel-Kırsal Kalkınma Bakanlığınca hazırlanan “Beton dolgulu çelik tüp yapılar için teknik kod” adlı kod dışında mevcut hükümlerin kapsamında yer almamaktadır. Ancak, eliptik BDÇT kolonların nihai dayanımının tayini için önerilen bu formül, kare kesitli BDÇT elemanların nihai dayanımının tahmin edilmesinde kullanılan formülün değiştirilmesi ile elde edilmiştir. Bu bağlamda, bu çalışmanın amacı eksenel yüklenmiş dikdörtgen ve dairesel kesitli BDÇT kolonlar için önerilen mevcut kod formüllerinin eliptik kesitli bu tarz kolonlara uygulanabilirliğini değerlendirmektir. Bunun için, 97 tane deneysel olarak test edilen BDÇT kolonundan oluşan bir data havuzu oluşturuldu. Burada, data seçimindeki ana kriter, eksenel yükleme durumuydu. Sonrasında, bu kod formüllerinin tahmin performansı istatistiksek parametreler nezdinde değerlendirildi. Sonuçlar dairesel kesitli BDÇT kolonlar için önerilen kod formüllerinin dikdörtgen kesitli olanlar için önerilenlerden daha iyi tahmin kapasitesine sahip olduğunu gösterdi. Dairesel kesitli BDÇT kolonları için önerilen bu tasarım formülleri arasında ise en iyi tahmin edebilme kapasitesine, Amerikan Çelik Yapı Enstitüsü, İngiliz Standart Enstitüsü, Kanada Standartlar Birliği ve Avrupa Standartları tarafından önerilen formülleri sahipti. Bu kod formülleri en düşük ortalama mutlak yüzde hata değerlerine ve 0.8’den yüksek R-kare değerlerine sahipti.

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1. INTRODUCTION (GİRİŞ)

The concrete-filled steel tubular (CFST) columns were first utilized in the construction of the Severn railway bridge in the United Kingdom in 1879. The additional studies in this field were carried out during the 1960s in Russian, West Europe, North America, and Japan. But the difficulties, especially concrete casting-concerned, in the manufacturing of these columns restricted the understanding of the structural behavior of such members and so, caused them to be used for architectural purposes. However, the use of the CFST columns in the high-rise buildings, long-span bridges, and heavy industry structures became prevalent accompanied by the developments in the pumpability of the concrete and easily manufacturing ability of the high-strength concretes in the 1980s [1]. By starting the understanding of such members with regard to structural behavior, it was revealed in consequence of studies that these members provide advantages not only from the point of aesthetics but also in terms of design stages for structural applications [2-4].

The CFST columns are composite structural members famed for high strength and ductility, and during the earthquake, high energy absorption characteristics [5]. Besides, co-utilization of concrete and steel in this manner provides the opportunity for the manufacturing of composite structural members with superior load-carrying capacity and resistant-to-flexural performance [1,3,6,7]. Also, they exhibit better deformation and toughness performances compared to the traditional columns [8]. In addition to the mechanical benefits, such structural members offer structural advantages such as a quicker and more economical production since the steel tube plays a permanent formwork role during the manufacturing of columns [4,7]. Another significant benefit provided by these structural members is to be more fire-resistant members [3].

The CFST columns can be produced in circular, square, and rectangular sections, as respectively displayed in Figure 1. Since the steel tube in the circular section provides a uniform confinement effect, it was found that the CFST columns with a circular section exhibit better performance than those with other sections [3]. Square and rectangular CFST columns have also familiar advantages such as high ductility and energy absorption capacity as circular CFST columns have [3]. But, the CFST columns with the square or rectangular sections have some disadvantages like cracks occurring depending on the stress concentration at the corner of the steel tubes [10,11].

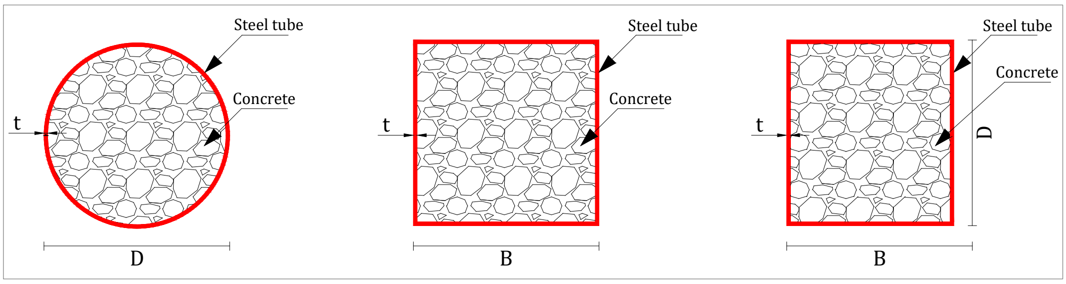
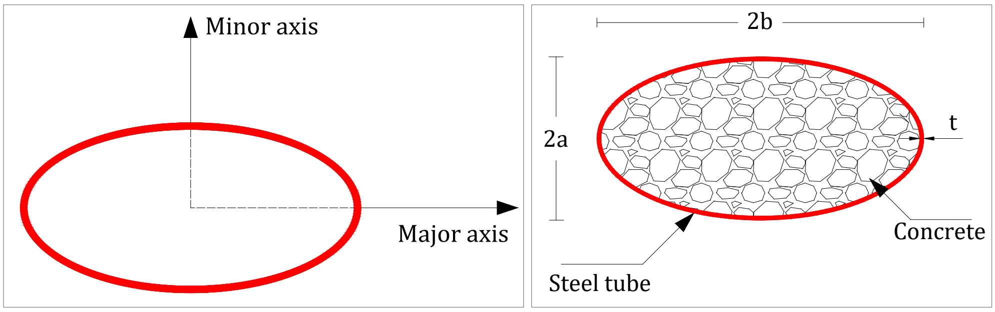


Figure 1. *The typical cross-section view of CFST columns [9]*

The elliptical hollow profile is a relatively new and rare used section that was added to existing sections [2,6]. The elliptical hollow section is the newest member of the structural steel hollow section family that consisted of the circular hollow section in the first stage and then, included also the square and rectangular hollow sections [12-14]. The elliptical hollow section has engaged the attention of architects and engineers due to not only its aesthetic appeal but also its structural efficiency and other advantages that it provided [1,3,6,7]. This section attains its aesthetic appeal from its circular section appearance, and its structural efficiency and advantages from the rectangular section outlook, which provides it to have major and minor axes as demonstrated in Figure 2a [1]. The unfilled elliptical hollow sectioned structural members have been employed in a series of applications [1,15,16]. Despite the fact that the utilization of the members having this section for structural purposes is prevalent, its behavior under loads, and usage conditions and manner are not in the scope of any design code and standard [1]. But various experimental and numerical studies examining the behavior of structural members having the elliptical hollow section under different loading conditions are available in the literature [1-4,6-8,12,14,16]. In addition to classifying the elliptical hollow sections [17], the behavior under several loading conditions such as the compressive [18], shear [19], bending [20], flexural buckling [21], elastic buckling under compression [22,23], and combined compressive and uniaxial buckling [24] has been experimentally investigated in these studies. These conducted studies have shown that the elliptical hollow section exhibits a mechanical performance between the rectangular and circular sections. In another word, the elliptical section has major and minor axes without having sharp corners, thus conducing to the elliptical section performing better than the rectangular section, on the other hand, its both compressive strength and mechanical performance becomes lower than the circular section since the confinement effect in this section is not completely provides as in the circular section. However, the greatest efficiency of the elliptical section in structural meaning is having different carrying capacities through the major and minor axes. Hence, by increasing the size through any axis, the load-carrying capacity in that axis can be enhanced by virtue of this characteristic. On the other hand, in the circular section, increasing the size is biaxial due to the constant radius, so desiring to increase the load-carrying capacity in any axis would lead to increasing the load-carrying capacity in the other axis, and this is the biggest disadvantage of the circular section [25].



(a) (b)

Figure 2. *Elliptical: (a) hollow section view and (b) concrete-filled section view*

The knowledge and experiences achieved from the experimental investigation of the behavior of the elliptical hollow section and its utilization in structural meaning have paved the way for manufacturing and investigating the elliptical CFST members. The behavior of the elliptical CFST columns under axial and eccentric loadings has been investigated by some researchers [1,6,14,25,26]. Also, it was reported that the structural behavior of the elliptical CFST columns should be detailed examined and prediction models should be developed [6]. For the present, there is currently no application code, specification, and/or standard concerned with the design of the elliptical compression members, except the code called "Technical code for concrete-filled tubular structures" prepared by the Ministry of Housing and Urban-Rural Development of the People's Republic of China [27]. But, the formula proposed by this technical code for predicting the ultimate axial strength of the elliptical CFST columns was achieved by modifying the formula proposed by the China military code [28] for predicting the ultimate axial strength of the square CFST columns. For this reason, utilization of such members for structural purposes is possible only by considering the results achieved from the experimental works and numerical methods developed by taking into account these results. Within this scope, some researchers have used the formulae suggested by codes or standards for the determination of the ultimate axial strength of the CFST columns with the square, rectangular, or circular sections in the prediction of the load-carrying capacity of the elliptical CFST columns subjected to axial load. In these studies [1-4,6-8,14-16,25], the ultimate axial strength values determined by using the formulae suggested by the design codes for the prediction of the ultimate axial strength of the different sectioned CFST columns were compared to the experimental ones and then, the possible usability and efficiency of these formulae were evaluated.

In this context, a data repository consisting of the properties and ultimate axial strength of the experimentally investigated CFST columns having an elliptical section has been gleaned. Then, the code formulae employed by the researchers in the determination of the ultimate axial strength of the elliptical CFST columns have been applied to this data repository in order to assess the prediction performance and efficiency of these formulae. In this way, instead of a study-based assessment of the code formulae, their wide data-based assessment has been carried out. The code formulae proposed by the Ministry of Housing and Urban-Rural Development of the People's Republic of China (abbreviated as ***GB***) [27], American Concrete Institute (abbreviated as ***ACI***) [29], American Institute of Steel Construction (abbreviated as ***AISC***) [30], Architectural Institute of Japan (abbreviated as ***AIJ***) [31], British Standards Institute (abbreviated as ***BSI***) [32], Canadian Standards Association (abbreviated as ***CSA/01*** and ***CSA/09***) [33,34], and European Standards (abbreviated as ***EC4***) [35] for the design of the rectangular- (or square) and circular-sectioned CFST columns have been handled in the current study. The prediction performance of these design formulae has been assessed in terms of some statistical parameters.

2. DESIGN FORMULAE OF CODES (KODLARIN TASARIM FORMÜLLERİ)

Herein, the elliptical section, rectangular (or square) section, and circular section are abbreviated as ES, RS, and CS, respectively. Within the aforementioned codes, the formula for the elliptical section has been proposed by only the ***GB*** [27] while the others have been suggested for the rectangular (square) and circular sections. The ***GB*** code formula proposed for the design of the elliptical CFST columns is as follows [27]:

$$N_{GB,ES} = f_{sc}(A_s + A_c) \qquad 2.1$$

here;

f_{sc} is used to describe the strength of the composite section, and to be determined as follows:

$$f_{sc} = (1{,}212 + B\xi + C\xi^2)f_c \qquad 2.1a$$

in which;

B and C are the coefficients developed for the elliptical section, and to be determined by Equation 1b and 1c, respectively:

$$B = \left(\frac{0{,}176 f_y}{213} + 0{,}974\right)\left(\frac{b}{a}\right)^{0{,}3} \qquad 2.1b$$

$$C = \left(-\frac{0{,}104 f_c}{14{,}4} + 0{,}031\right)\left(\frac{b}{a}\right)^{0{,}3} \qquad 2.1c$$

ξ is the confinement factor, and to be determined as follows:

$$\xi = \frac{A_s f_y}{A_c f_c} \qquad 2.1d$$

f_y and f_c are the yield strength of the steel tube and concrete compressive strength measured on ϕ150x300-mm cylindrical specimen, respectively.

A_s and A_c are the cross-section area of the steel tube and concrete, respectively, and to be determined as follows:

$$A_c = \pi(a - t)(b - t) \qquad 2.1e$$

$$A_s = P_m t \qquad 2.1f$$

here;

a and b are the major and minor outer radius of the elliptical section, and t is the thickness of the steel tube, as indicated in Figure 2b, and P_m is the average perimeter of the elliptical-sectioned steel tube, and to be determined by Equations 1g-:

$$P_m = \pi(a_m + b_m)(1 + 0{,}25h_m) \qquad 2.1g$$

$$a_m = \frac{2a - t}{2} \qquad 2.1h$$

$$b_m = \frac{2b - t}{2} \qquad 2.1i$$

$$h_m = \frac{(a_m - b_m)^2}{(a_m + b_m)^2} \qquad 2.1j$$

ACI [29] recommends handling Equation 2 in the determination of the ultimate axial strength of concrete columns (without discriminating the section type) reinforced by steel and the individual strengths of concrete and steel have been superposed in this presented formula:

$$N_{ACI} = A_s f_y + 0,85 A_c f_c \tag{2.2}$$

AISC [30] has proposed Equation 2 for the design of the rectangular-sectioned CFST columns subjected to the axial compressive load while for the circular-sectioned CFST columns, it has been suggested another equation, in which the constant coefficient of the concrete is increased to 0.95 due to confinement effect, as presented follows:

$$N_{AISC,RS} = A_s f_y + 0,85 A_c f_c \tag{2.3}$$

$$N_{AISC,CS} = A_s f_y + 0,95 A_c f_c \tag{2.4}$$

AIJ [31] has suggested two different formulae (varying by section type) for the determination of the ultimate axial strength of the CFST columns. The formula for the rectangular-sectioned CFST columns is presented in Equation 5 and that for the CFST columns with the circular section is given in Equation 6. The formula proposed for the squared-section CFST columns is identical to that proposed by ***ACI*** [29] and ***AISC*** [30]. The only difference is in the determination of steel and concrete. However, in the formula suggested by ***AIJ*** [31] for the circular-sectioned CFST columns, the strength provided by the steel tube has been increased by 27% due to the confinement effect. The equations are presented as follows:

$$N_{AIJ,RS} = A_s + 0,85 A_c f_{ck} \tag{2.5}$$

$$N_{AIJ,CS} = 1,27 A_s f_s + 0,85 A_c f_{ck} \tag{2.6}$$

here;

f_s is the smaller one of steel yield strength or 70% of the steel ultimate tensile strength, and f_{ck} is the concrete compressive strength measured on ϕ100x200-mm cylindrical specimen.

BSI [32] has recommended a code for the design of steel, concrete, and composite bridges. In this code, Equations 7 and 8 have been proposed for the prediction of the ultimate strength of the rectangular- and circular-sectioned CFST columns under axial loading, respectively:

$$N_{BSI,RS} = 0,95 A_s f_y + 0,45 A_c f_{cu} \tag{2.7}$$

here;

f_{cu} is the 28-day concrete characteristic compressive strength measured on the cubic specimen.

$$N_{BS,CS} = 0,95 A_s f_y' + 0,45 A_c f_{cc} \tag{2.8}$$

here;

f_{cc} is the triaxially contained concrete enhanced characteristic compressive strength under axial load and f_y' is the reduced yield strength of steel, and to be determined by Equations 8a and 8b, respectively:

$$f_{cc} = f_{cu} + C_1 \frac{t}{D} f_y \tag{2.8a}$$

$$f_y' = C_2 f_y \tag{2.8b}$$

in which;

C_1 and C_2 are the constants defined in ***BSI*** [32] in regard to the effective length-to-diameter ratio (L_e/D_e) of the column. Normally, D is the outer diameter of the circular steel tube, however, the equivalent diameter (D_e) for the elliptical section will be used in the formulae proposed by ***BSI*** [32]. For this reason, the equations recommended by Yang et al. [1] can be used in the determination of D_e, as given in Equations 8c and 8d. Yang et al. [1] have also stated that if D_e is going to be used in the calculation of the effective length-to-diameter ratio, it can be calculated regarding Equation 8c, and if D_e is going to be used in the determination of the enhanced characteristic strength of triaxially contained concrete under axial load, Equation 8d can be employed:

$$D_e = 2b \tag{2.8c}$$

$$D_e = \frac{P_m}{\pi} \tag{2.8d}$$

In 2001, ***CSA/01*** [33] has proposed Equations 9 and 10 for the determination of the ultimate axial strength of the CFST columns with the rectangular and circular sections, respectively:

$$N_{CSA/01,RS} = A_s f_y + 0{,}85 A_c f_c \tag{2.9}$$

$$N_{CSA/01,CS} = \tau A_s f_y + (\tau')_{CSA/01} 0{,}85 A_c f_c \qquad L/D_e < 25 \tag{2.10}$$

in which;

$$\tau = \frac{1}{\sqrt{1+\rho+\rho^2}} \tag{2.10a}$$

$$\rho = 0{,}02(25 - L/D_e) \tag{2.10b}$$

$$(\tau')_{CSA/01} = 1 + \left(\frac{25\rho^2\tau}{D_e/t}\right)\left(\frac{f_y}{0{,}85 f_c}\right) \tag{2.10c}$$

here;

L is the laterally unbraced length of the column, here, Zhao and Packer [14] have proposed Equations 10d and 10e for the determination of the effective diameter of an elliptical section when it is needed to be used in the formulae suggested by ***CSA/01*** [33]:

$$D'_e = 2a[1 + f(a/b - 1)] \tag{2.10d}$$

$$f = 1 - 2{,}3(t/2a)^{0{,}6} \tag{2.10e}$$

Additionally, in 2009, ***CSA/09*** [34] has proposed another two formulae for the determination of the ultimate axial strength of the CFST columns with the rectangular and circular sections. In these formulae, a small revision has been done for the coefficient that is used in the calculation of the contribution of concrete to the composite section, as presented below:

$$N_{CSA/09,RS} = A_s f_y + \alpha_1 A_c f_c \tag{2.11}$$

in which;

$$\alpha_1 = 0{,}85 - 0{,}0015 f_c \geq 0{,}67 \tag{2.11a}$$

$$N_{CSA/09,CS} = \tau A_s f_y + (\tau')_{CSA/09} \alpha_1 A_c f_c \qquad L/D_e < 25 \tag{2.12}$$

in which;

$$(\tau')_{CSA/09} = 1 + \left(\frac{25\rho^2\tau}{D_e/t}\right)\left(\frac{f_y}{\alpha_1 f_c}\right) \tag{2.12a}$$

In final, the formulae proposed by ***EC4*** [35] for the determination of the ultimate strength of the rectangular- (or square) and circular-sectioned CFST columns subjected to axial load have been presented herein. Some researchers [1,3,6,14,15] have modified the design formula for the CFST columns with rectangular/square sections to be applicable to the elliptical-sectioned CFST columns. They made this modification since the steel tube having the elliptical section provides more confinement than that having the rectangular/square section. Regarding this modification, the following expression has been obtained:

$$N_{EC4,RS} = A_s f_y + A_c f_c \tag{2.13}$$

Besides, ***EC4*** [35] suggests two formulae depending on the relative slenderness ($\bar{\lambda}$) value for the CFST columns with the circular section. Based on this criterion, when the $\bar{\lambda}$ value is greater than 0.5, Equation 13 can be handled to determine the ultimate axial strength of the CFST columns with the circular section, too. However, otherwise, Equation 14 has been suggested for the design of the CFST columns with the circular section, as presented follows:

$$N_{EC4,CS} = \eta_s A_s f_y + A_c f_c \left[1 + \eta_c \left(\frac{t}{D_e}\right)\left(\frac{f_y}{f_c}\right)\right] \tag{2.14}$$

here;

Apart from Equations 10d-e, there are two new recommendations for the determination of the equivalent diameter of the elliptical section when it is needed to be used in the formulae proposed by ***EC4*** [35].

One has been recommended by Liu et al. [15] and the other one has been recommended by Corus [36], as given in Equations 14a and 14b, respectively:

$$D_e' = \frac{2a^2}{b} \tag{2.14a}$$

$$D_e' = 2a\sqrt{\frac{a}{b}} \tag{2.14b}$$

η_s and η_c are the reduction factor for the steel section and the enhancement factor for the concrete section, respectively, and to be determined by handling Equations 14c and 14d, respectively.

$$\eta_s = 0{,}25(3 + 2\bar{\lambda}) \qquad (\leq 1{,}0) \tag{2.14c}$$

$$\eta_c = 4{,}9 - 18{,}5\bar{\lambda} + 17\bar{\lambda}^2 \qquad (\geq 1{,}0) \tag{2.14d}$$

in which;

$$\bar{\lambda} = \sqrt{\frac{N_{pl,Rd,(6.30)}}{N_{cr}}} \tag{2.14e}$$

here;

$N_{pl,Rd,(6.30)}$ is the plastic resistance at the characteristic value presented in ***EC4*** [35], and to be determined by the following equation:

$$N_{pl,Rd,(6.30)} = A_s f_y + 0{,}85 A_c f_c \tag{2.14f}$$

N_{cr} is the elastic critical normal force for relevant buckling mode, and to be determined by the following equation:

$$N_{cr} = \frac{\pi^2 (EI)_{eff}}{(KL)^2} \tag{2.14g}$$

here;

K is the effective length factor (can be taken as 1.0 for pin-pin connection)

$(EI)_{eff}$ is the effective stiffness of the composite section), and to be determined by the following equation:

$$(EI)_{eff} = E_s I_s + K_c E_c I_c \tag{2.14h}$$

here;

E_s and E_c are the modulus of elasticity of the steel tube and concrete, respectively, and I_s and I_c are the second moments of area of the steel tube and concrete, respectively, and K_c is the correction factor (taken as 0.6). If the modulus of elasticity of the concrete is not provided, the following empirical expression proposed by ***AISC*** [30] can be used to determine it:

$$E_c = w_c^{1,5} 0{,}043\sqrt{f_c} \tag{2.14i}$$

here;

w_c is the unit weight of the concrete (can be taken between 2300 and 2500 kg/m^3)

In conclusion, the ultimate axial strength determined by Equation 14 is multiplied by a reduction coefficient (χ) for the relevant buckling mode. It should be noted that when the $\bar{\lambda}$ is less than or equal to 0.2, the buckling effect can be neglected, hence χ can be taken as 1.0 [3]. Eurocode 3 [37] has proposed the following expression for computing the χ:

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} \quad but\ \chi \leq 1.0 \tag{2.14j}$$

in which;

$$\phi = 0.5\left[1 + \alpha(\bar{\lambda} - 0.2) + \bar{\lambda}^2\right] \tag{2.14k}$$

here;

α is the defectiveness factor affiliated to the buckling curve, can be taken from Table 6.1 presented in Eurocode 3 [37].

3. PRESENTATION OF DATA REPOSITORY (VERİ HAVUZUNUN SUNUMU)

In this study, the data has been selected regarding two basic criteria that are the elliptical section and axially loading condition. In this way, a total of 97 CFST columns with the elliptical section have been gathered up to constitute the data repository [1,2,4,6-8,14-16,25]. The data have been obtained from the experimental studies available in the literature. The summary of the data repository and the source of each data are presented in Table 1. Since the aforementioned formulae proposed by the design codes require the major and minor outer diameters of the section, thickness and yield strength of the steel tube, the compressive strength of the concrete, and column height to predicted the ultimate axial strength, these properties of the elliptical CFST columns have been presented in Table 1.

Table 1. *Summary of data repository gleaned from experimental studies*

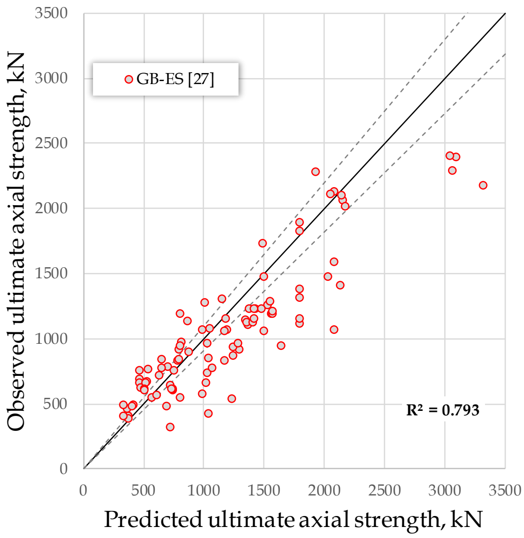
Source	Data #	Steel tube				Concrete compressive strength, f_c (MPa)	Column height, H (mm)	Ultimate axial strength, N_u (kN)
		Major diameter, $2a$ (mm)	Minor diameter, $2b$ (mm)	Thickness, t (mm)	Yield strength, f_{sy} (MPa)			
Yang et al. [1] Lam and Testo [2] Dai and Lam [7]	9	148.78-150.57	75.35-75.74	4.18-6.43	369-400.5	30.5-102.2	300	839.0-1483.0
Ren et al. [4]	6	192.0	124.0	3.82	439.3	61.0	1800-3600	1121.0-1896.0
Jamaluddin et al. [6]	24	150.0-197.8	75.0-100.3	4.0-5.2	361.7-424.4	13.0-90.0	299-2502	326.6-2116.0
Uenaka [8]	21	158.0-160.8	63.1-107.8	1.0-2.3	201-341	25.0-27.3	160-250	389.1-921.3
Zhao and Packer [14]	8	150.05-220.7	75.21-110.7	4.51-9.72	358-421	48.2-69.2	500-600	1075.0-2290.0
Liu et al. [15]	15	137.5-318.5	68.0-155.0	2.58-2.62	376.4	63.1	279-636	610.4-2408.4
Mahgub et al. [16]	8	150.0-250.0	75.0-125.0	6.3-7.1	384.8-424.4	45.0-103.75	1500-2500	556.0-2184.4
Lam et al. [25]	6	85.4-124.0	57.0-78.4	1.88-3.20	339-420	37.0-90.0	174-244	412.3-1064.8

The column specimens have major outer diameters ranging between about 85 and 320 mm and minor outer diameters varying between about 55 and 160 mm. The steel tubes used in these studies have thickness values ranging from about 1 to 10 mm and yield strength values between about 200 and 440 MPa. The lowest compressive strength used as infill material in the manufacturing of the elliptical CFST columns is 13 MPa, whereas the highest compressive strength value is almost 104 MPa. In these studies, the elliptical CFST columns have been manufactured in the height changing between 160 and 3600 mm. By these sectional and mechanical properties, the ultimate axial strength values varying between 326.6 and 2408.4 kN have been achieved. The researchers found out that increasing compressive strength of the concrete leads to enhancing the load-carrying capacity of such columns [1,2,4,6,16,25]. In addition, it was reported that increasing the thickness and yield strength of the steel tube significantly conduce to an increase in the ultimate axial strength of the elliptical CFST columns [1,2,4,8,14,25]. Another important finding reported in these studies is that increasing the column height causes a reduction in the load-carrying capacity, whereas increasing the diameters of the elliptical section in both axes by keeping the aspect ratio (2a/2b) constant results in enhancing the ultimate axial strength [6,14,16,25].

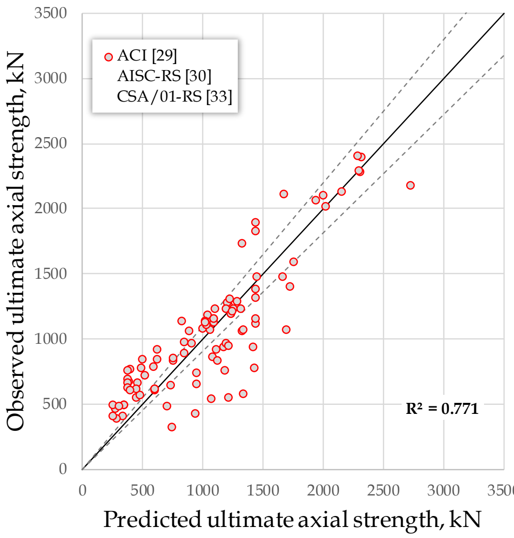
4. RESULTS AND DISCUSSION (BULGULAR VE TARTIŞMA)

The observed ultimate axial strength values of the elliptical CFST columns versus the predicted values are presented in Figures 3a-l. In these figures, the degree of correlation between the observed and predicted values is assessed in terms of the coefficient of determination (R-squared) values that is a useful tool for comprehending such type of relationship. The R-squared value for each formula was determined by using Equation 15. In a normal relationship, the R-squared can value between 0 (no relationship) and 1 (exact relationship). The results obtained from the formula proposed by ***ACI*** [29] and formulae suggested by ***AISC*** [30] and ***CSA/01*** [33] for the RS are the same, hence, their results have been plotted on the same graph, as shown in Figure 3b. Regarding the R-squared values, it can be expressed that in the general sense, the prediction performance of the formulae proposed for the RS can be considered moderate since their R-squared values are less than 0.8. The formulae suggested for the CS have relatively better prediction performance. Among these formulae of the CS, the best prediction performance was achieved from the formula proposed by ***AISC*** [30] with an R-squared value of 0.839, however, the R-squared values of the formulae suggested by ***BSI*** [32], ***CSA/01*** [33], and ***EC4*** [35] for the CS are also greater than 0.8. Besides, it can be also seen that although the design formula recommended by ***GB*** [27] for the ES has a slightly better prediction performance than the formulae proposed by other design codes for the RC, its prediction performance can be considered relatively poor when it is compared to the formulae suggested by other design codes for the CS.

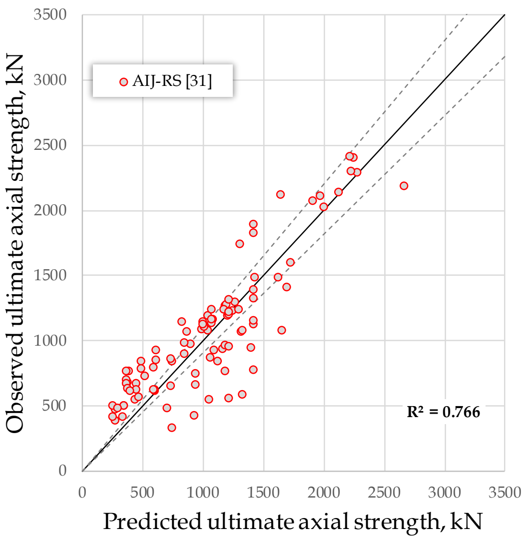
$$R-squared=\left(\frac{\sum(m_i-m)(p_i-p)}{\sqrt{\sum(m_i-m)^2\sum(p_i-p)^2}}\right)^2 \quad 4.1$$



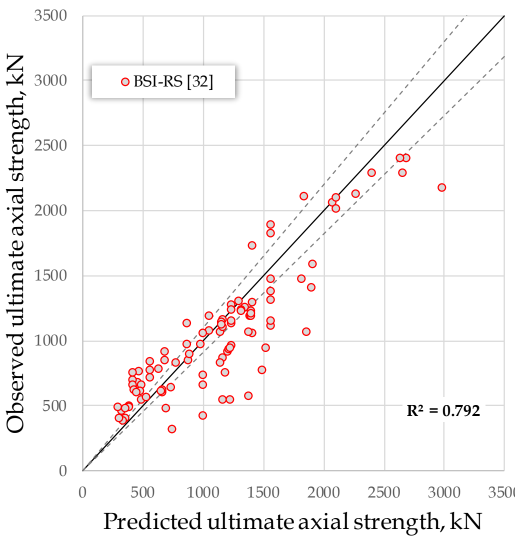
(a)



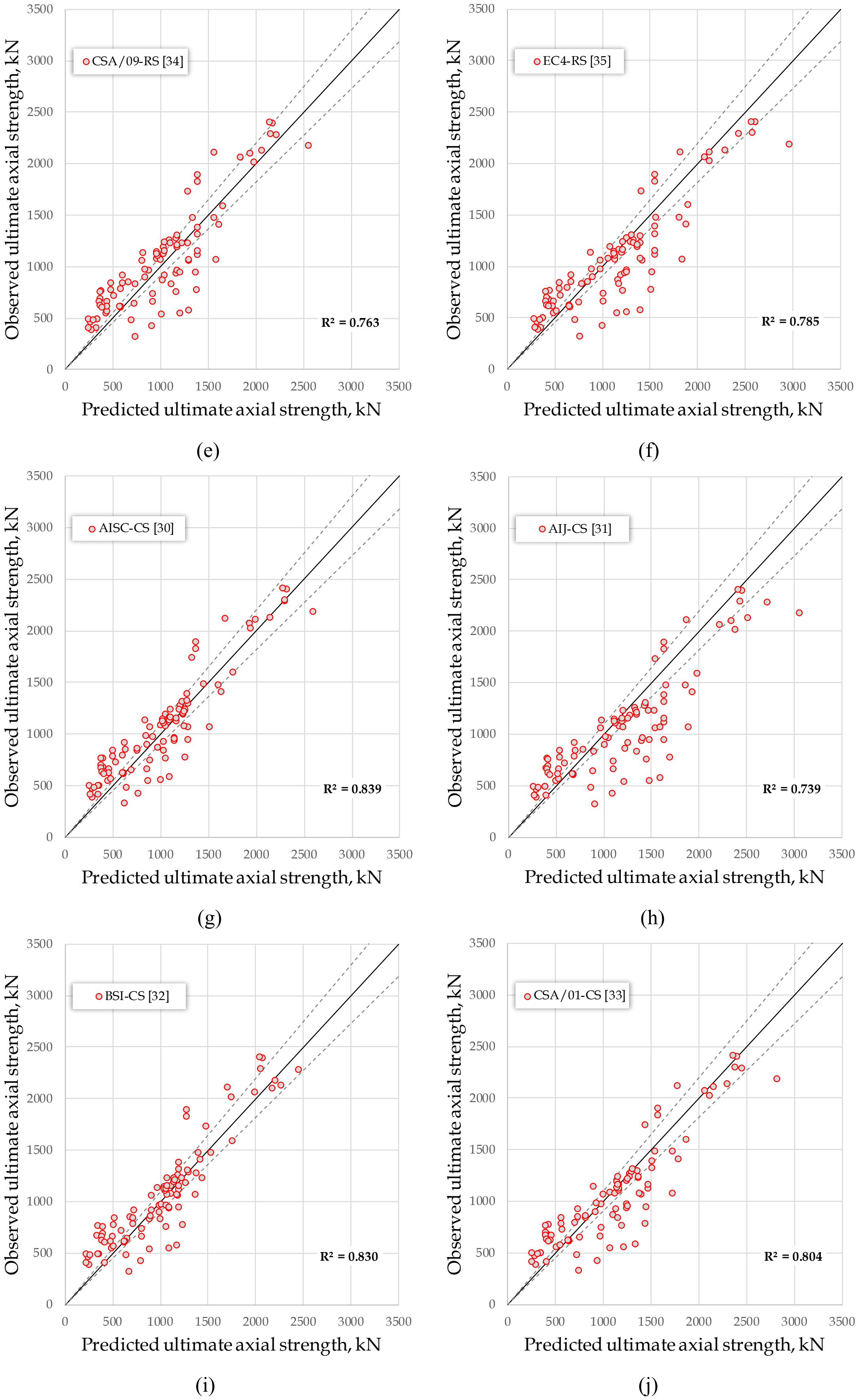
(b)

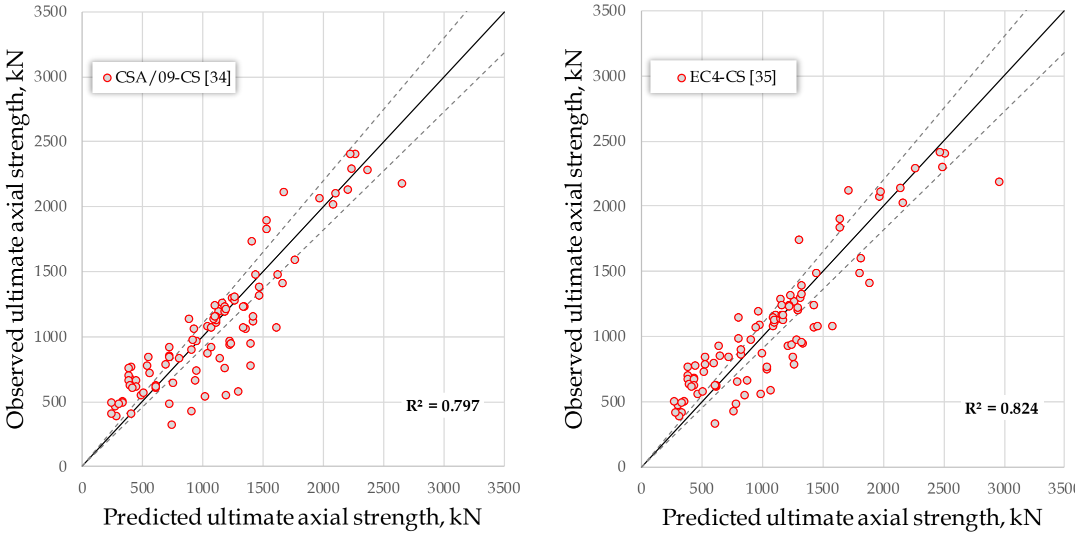


(c)



(d)


CSA/09-RS [34]
R² = 0.763
(e)
EC4-RS [35]
R² = 0.785
(f)
AISC-CS [30]
R² = 0.839
(g)
AIJ-CS [31]
R² = 0.739
(h)
BSI-CS [32]
R² = 0.830
(i)
CSA/01-CS [33]
R² = 0.804
(j)
Observed ultimate axial strength, kN
Predicted ultimate axial strength, kN
0
500
1000
1500
2000
2500
3000
3500



(k) (l)

Figure 3. *Observed versus predicted ultimate axial strengths obtained from formula proposed by: (a) GB [27] for ES, (b) ACI [29], AISC [30] for RS, and CSA/01 [33] for RS, (c) AIJ [31] for RS, (d) BSI [32] for RS, (e) CSA/09 [34] for RS, (i), (f) EC4 [35] for RS, (g) AISC [30] for CS, (h) AIJ [31] for CS, (i) BSI [32] for CS, (j) CSA/01 [33] for CS, (k) CSA/09 [34] for CS, and (l) EC4 [35] for CS*

Apart from the R-squared values, when the dispersion of the data is visually observed, it can be seen that generally, the formulae for the RS have wide-dispersed data, especially for the ultimate axial strength values less than 2000 kN. In other words, the differences between the predicted and observed ultimate axial strength values are frequently more than 10% when the ultimate axial strength values are less than 2000 kN and the formulae for the RS are employed for the prediction. An identical observation can be also seen in Figure 3h in which the ultimate axial strength values are predicted by the formula proposed by ***AIJ*** [31] for the CS. From a general perspective, it can be stated that the formulae given by ***AIJ*** [31] have a poor prediction performance for such types of composite columns. Besides, it has been seen from the visual observation that the experimental versus predicted data scatterings achieved from the formulae of *AISC* [30] and *BSI* [32] for the CS are in a comparatively more narrow range.

To comprehensively compare the prediction performance of the code formulae, some statistical parameters such as mean absolute percent error (MAPE), normalized root mean square error (nRMSE), fitness function, performance index (PI), mean normalized strength, minimum and maximum normalized strengths, standard deviation (SD) and coefficient of variation (CoV) in normalized strength, and overpredicted percentage have been determined. MAPE is another expression manner of the mean absolute error, however, in MAPE, the difference between the actual and predicted values is divided by the actual value to achieve the relative difference, as presented in Equation 16. Generally, it can be stated that the smaller the MAPE, the better the prediction performance. nRMSE is achieved by dividing the root mean square error value by the mean actual value, and it is determined by Equation 17. When the model has an nRMSE value between 0 and 0.1, the prediction performance of the model can be considered “excellent”. In the case of nRMSE value between 0.1 and 0.2, the prediction performance of the model can be considered “good”, whereas, in the case of between 0.2 and 0.3, it can be stated that the model has a “moderate” prediction performance. But when the nRMSE value is greater than 0.3, the prediction performance of the model is accepted as “poor or bad”.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{m_i - p_i}{m_i}\right| x100 \qquad 4.2$$

$$nRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}(m_i - p_i)^2}{n}}}{\bar{m}} \qquad 4.3$$

Herein, a fitness function has been adopted to observe the prediction performance of the design formulae proposed by codes. Therefore, the expression given in Equation 18 has been employed in the determination of the fitness function value of the formulae. As can be seen from the equation, the adopted fitness function consists of R-squared and nRMSE values. It is well-known that the ideal values for the R-squared and nRMSE parameters are 1.0 and 0, respectively, which means the optimum value for the fitness function can be 1.0 when the following equation is taken into consideration.

$$Fitness = \frac{1}{R^2} + nRMSE \tag{4.4}$$

Another parameter handled to evaluate the prediction performances of the code formulae is the PI value that has been determined by using Equation 19. As can be seen from the expression, nRMSE and R-squared values are employed in the determination of the PI value. It is obvious that the minimum value for the PI can be 0 and this value can be achieved when the nRMSE value is determined as 0. In other words, when the aggregate residual error between the actual and predicted values approaches 0, the PI value approaches 0, too. For this reason, it can be stated that the lower the PI value, the more accurate the prediction.

$$PI = \frac{nRMSE}{R+1} \tag{4.5}$$

All the statistical parameters determined in this study for assessment of the prediction performance of the code formulae have been presented in Table 2. As can be seen from the table, generally, the formulae proposed for the RS yielded worse statistical parameters. Relying on the statistical parameters, it can be expressed that the prediction performance of the formulae suggested for the SC was better than those suggested for the RC. For example, the lowest MAPE value was seen in the formula proposed by ***BSI*** [32] for the CS, whereas the lowest nRMSE, fitness function, PI, and highest R-squared values were observed in the formula proposed by ***AISC*** [30] for the CS. However, the lowest overprediction percentage was achieved from the formula suggested by ***CSA/09*** [34] for the RC, and the third and fourth smallest overprediction percentages were obtained from the formula suggested by ***AIJ*** [31] for the RC and ***ACI*** [29] (***AISC*** [30] and ***CSA/01*** [33] for the RC), respectively. The formula proposed by ***GB*** [27] for the ES had an overprediction of more than 50%. In addition, the overprediction value of the formula proposed by ***BSI*** [32] and ***EC4*** [35] for the RS and ***AIJ*** [31] and ***CSA/01*** [33] for the CS were also more than 50%. On the other hand, the highest minimum normalized strength value of 0.612 was achieved from the design formula recommended by ***GB*** [27] for the ES while the lowest maximum normalized strength value was obtained from the design formula recommended by ***AISC*** [30] for the CS.

Table 2. *Statistical parameters of design formulae proposed by codes*

Parameter		GB [27]	ACI [29] AISC [30] CSA/01 [33]	Formulae for rectangular section				Formulae for circular section					
				AIJ [31]	BSI [32]	CSA/09 [34]	EC4 [35]	AISC [30]	AIJ [31]	BSI [32]	CSA/01 [33]	CSA/09 [34]	EC4 [35]
MAPE		26.8_{2}	25.9_{7}	26.3_{5}	26.0_{6}	26.6_{3}	26.4_{4}	21.4_{11}	32.0_{1}	20.5_{12}	24.2_{8}	23.9_{9}	22.6_{10}
nRMSE		0.318_{2}	0.248_{5}	0.248_{6}	0.268_{4}	0.247_{7}	0.269_{3}	0.205_{12}	0.328_{1}	0.206_{11}	0.243_{8}	0.231_{9}	0.218_{10}
R-Squared		0.793_{7}	0.771_{4}	0.766_{3}	0.792_{6}	0.763_{2}	0.785_{5}	0.839_{12}	0.739_{1}	0.830_{11}	0.804_{9}	0.797_{8}	0.822_{10}
Fitness function		1.579_{2}	1.545_{5}	1.553_{4}	1.530_{7}	1.559_{3}	1.543_{6}	1.397_{12}	1.682_{1}	1.411_{11}	1.487_{8}	1.485_{9}	1.435_{10}
PI		0.168_{2}	0.132_{6}	0.132_{5}	0.142_{4}	0.132_{7}	0.143_{3}	0.107_{12}	0.176_{1}	0.108_{11}	0.128_{8}	0.122_{9}	0.119_{10}
Normalized	mean	1.131_{2}	1.012_{11}	0.992_{12}	1.085_{3}	0.974_{9}	1.085_{4}	0.959_{6}	1.154_{1}	0.965_{7}	1.066_{5}	1.028_{8}	0.987_{10}
	min	0.612_{12}	0.487_{5}	0.475_{2}	0.540_{11}	0.476_{3}	0.533_{10}	0.487_{4}	0.522_{9}	0.443_{1}	0.507_{8}	0.490_{6}	0.497_{7}
	max	2.421_{2}	2.301_{5}	2.274_{7}	2.359_{4}	2.257_{9}	2.403_{3}	1.887_{12}	2.768_{1}	2.053_{10}	2.293_{6}	2.271_{8}	2.008_{11}
	SD	0.343_{9}	0.377_{3}	0.375_{5}	0.377_{4}	0.369_{6}	0.387_{2}	0.290_{12}	0.463_{1}	0.303_{11}	0.366_{7}	0.358_{8}	0.313_{10}
	CoV	0.303_{11}	0.373_{4}	0.378_{3}	0.347_{7}	0.378_{2}	0.357_{5}	0.303_{12}	0.402_{1}	0.314_{10}	0.344_{8}	0.348_{6}	0.317_{9}
	Overpredicted	$58.8\%_{2}$	$37.1\%_{9}$	$34.0\%_{10}$	$54.6\%_{5}$	$30.9\%_{12}$	$55.7\%_{4}$	$33.0\%_{11}$	$62.9\%_{1}$	$39.2\%_{6}$	$55.7\%_{4}$	$38.1\%_{8}$	$38.1\%_{8}$
OVERALL		**53**	**64**	**62**	**61**	**63**	**49**	**116***	**19**	**101***	**79**	**88***	**105***

Note: values in red at the bottom-right corners show performance scoring; 1: the lowest-performing model, 12: the highest-performing model

As can be comprehended from the discussion given above, there is no only one design formula having the best statistical parameters. For this reason, in order to determine the best design formulae, a scoring system has been developed in the study herein. In this scoring system, each design formula takes a performance score for each statistical parameter according to its performance. Since there are 12 different design formulae, the scoring point has been designated as varying between 1 to 12, where 1 means the lowest-performing and 12 means the highest-performing. The scoring points have been presented in red at the bottom-right corner of each statistical parameter. In reference to this scoring system, the highest point has been collected by the design formula proposed by ***AISC*** [30] for the CS, and the design formulae suggested by ***EC4*** [35], ***BSI*** [32], and ***CSA/09*** [34] for the CS has respectively followed it. In a general sense, it can be expressed that if the determination of the ultimate axial strength of the elliptical CFST columns is required, the design formulae proposed by ***AISC*** [30], ***EC4*** [35], and ***BSI*** [32] and relatively ***CSA/09*** [34] for CS can be used.

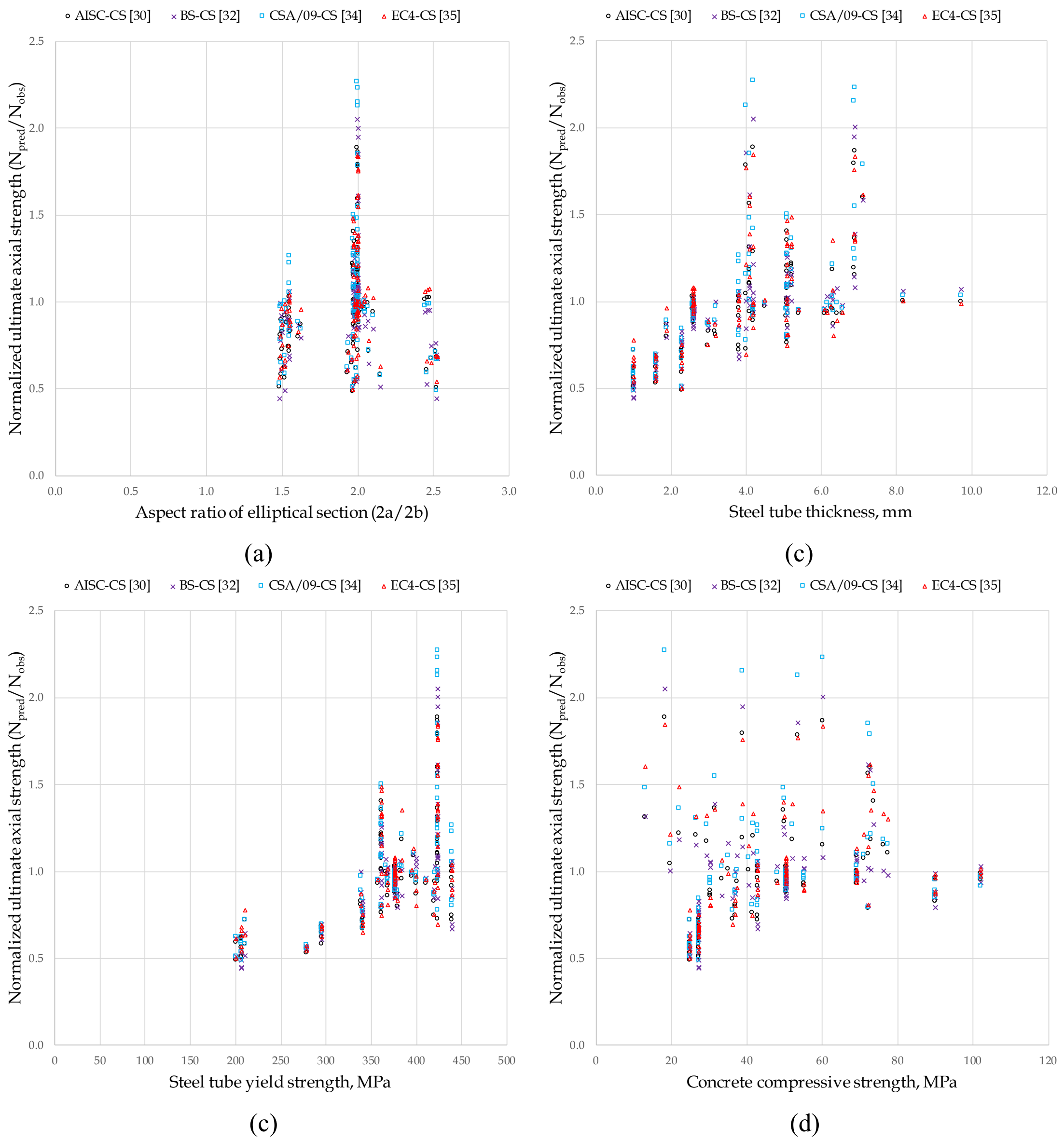


Figure 4. *Normalized ultimate axial strength versus: (a) aspect ratio of elliptical section, (b) steel tube thickness, (c) steel tube yield strength, and (d) concrete compressive strength*

In final, the normalized ultimate axial strength values attained from only these four formulae have been used to evaluate their prediction performance pursuant to the aspect ratio of the elliptical section, steel tube thickness, steel tube yield strength, and concrete compressive strength, as shown in Figures 4a, 4b, 4c, and 4d, respectively. Figure 4a displays the normalized ultimate axial strength dispersion in regard to the aspect ratio of the elliptical section. As can be seen, the aspect ratio values in the data repository compiled in this study are between almost 1.5 and 2.5. The dispersion in the figure shows that the code formulae have a relatively better prediction performance in terms of the dispersion of the normalized values when the aspect ratio of the section is around 1.5 or 2.5. However, in the case of the aspect ratio of 2.0, the normalized ultimate axial strength values dispersed in a wide range. The normalized strength dispersion obtained from the ***AISC*** [30] formula seems more narrow than the others at all aspect ratio levels. On the other hand, in Figure 4b, the normalized ultimate axial strength values versus steel tube thicknesses have been plotted. It is indicated that these formulae yield underprediction performance when the steel tube thickness is almost less than 4.0 mm, whereas they have generally overprediction performance when the thickness is almost more than 4.0 mm. Besides, the best prediction performance for all models is observed at the steel tube thicknesses between 2.0 and 4.0 mm, and more than 8.0 mm.

Figure 4c shows normalized ultimate axial strengths versus steel tube yield strengths. It can be stated that the code formulae have a relatively better prediction performance when the steel tube yield strength values are between 350 and 400 MPa. Moreover, it can be seen from the figure that when the steel tube yield strength decreases, the design formulae yield underprediction performance, whereas, at the high yield strength levels, the formulae proposed by the codes have frequently overprediction performance. Lastly, the normalized ultimate axial strengths versus concrete compressive strengths are demonstrated in Figure 4c. As can be easily sought from the figure that no relationship between the prediction performance of the design formulae and concrete compressive strength can be established. For all compressive strength values, the formulae have both over and underprediction performances.

5. CONCLUSIONS (SONUÇLAR)

Based on the aforementioned evaluations and findings, the following conclusions can be presented:

- The design formulae proposed for the CFST columns with rectangular (or square) sections resulted in lower prediction performance than that proposed for the circular sections.
- There was only one design model developed for the elliptical CFST columns. It was proposed by ***GB*** and its prediction performance also fell behind the design models suggested for the circular CFST columns.
- Among the design formulae proposed for the circular CFST columns, the one proposed by ***AISC*** had a relatively best prediction performance.
- When the overall statistical parameters determined in this study were taken into consideration, it was found out that the worst three prediction performances belong to the formulae proposed by ***AIJ*** for the circular section, ***EC4*** for the rectangular section, and ***GB*** for the elliptical section, whereas the best three prediction performances were achieved from the formulae suggested by ***AISC***, ***EC4***, and ***BSI*** for the circular section.

6. RECOMMENDATIONS FOR FURTHER STUDIES (İLERİ ÇALIŞMALAR İÇİN ÖNERİLER)

Regarding the finding presented above, it has been concluded that some of the existing square and circular section-based code formulae exhibit relatively good performance in the prediction of the ultimate axial strength of the elliptical CFST columns. However, an authentic model developed using soft-computing techniques for designing the elliptical CFST compression members would be a better solution instead of employing the existing square and circular section-based code formulae. For this reason, the authors recommend that developing a soft-computing-based model for the design of the elliptical CFST columns.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

The authors declare that there is no conflict of interest regarding the publication of the paper.

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