STRENGTH AND DUCTILITY ENHANCEMENT OF REINFORCED HSC COLUMNS CONFINED WITH HIGH-STRENGTH TRANSVERSE STEEL

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ABSTRACT: High-strength steel as transverse reinforcement is seldom used for confining steel in high-strength concrete columns. The behavior of structural components as a consequence of the use of a combination of high-strength concrete and steel is still not well known. To obtain an accurate ductility of high-strength concrete confined columns, it requires an analytical stress-strain model of confined concrete which is capable of describing an actual strength and ductility behavior. In this paper, an analytical stress-strain relationship for confined high-strength concrete is proposed. The model is found to provide a reasonably good prediction of the available experimental data of circular and square high-strength concrete column specimens confined by high-strength transverse steel with various configurations. The proposed model is based on the extensively obtained data from tests of column specimens subjected to concentric compression loading. The model can also be used for concrete columns confined by spirals or circular hoops, rectilinear hoops, crossties, and combinations of these reinforcements.

KEYWORDS: Column, confined concrete, ductility, high-strength concrete, high-strength transverse steel, stress-strain relationship.

1. INTRODUCTION

The use of high-strength steel for transverse steel as confining steel in HSC columns has not been widely investigated. The behavior of structural components using both high-strength concrete and transverse steel has not been well known so far. To date, there is no confinement model available that is capable of accurately describing the ductility and strength of HSC columns confined with high-strength steel. The model can also be implemented either for circular or square column sections.

The primary aim of this paper is to propose a more rational analytical stress-strain model that is capable of describing the actual confinement phenomenon of HSC columns confined by high-strength steel. Another objective is to compare the confinement models available in literature with the experimental results obtained from the study conducted by several researchers worldwide. The proposed model is obtained by modifying the model proposed earlier by Razvi and Saatcioglu [1] using a large number of experimental data from several researchers. The proposed model has been well verified using 102 square and circular column specimens tested under monotonic axial loading. This study only concentrates on HSC column specimens confined by high-strength transverse steel. The concrete strength ranges from 50 to 128 MPa, whereas the yield strength of the transverse steel is between 570 and 1387 MPa with the volumetric ratio of 0.32 to 5 percent.

From the analytical result, it can be concluded that there is significant difference between the predictions from several selected confinement models and the experimental results, particularly in the descending branches of the stress-strain curves. According to the statistical evaluation, a model which

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is developed based on the modified Razvi and Saatcioglu [1] model is proposed. The proposed model can be used to predict the actual confinement effect on both square and circular HSC columns confined by high-strength transverse steel. The peak strength corresponding peak strain and ductility enhancement factor of the stress-strain relationship are presented in a comparative study for different confinement situations.

2. CONFINED RC COLUMNS

2.1. Circular Columns

For circular columns, the lateral confinement resulted from the spiral can be assumed to be uniformly distributed over the outer perimeter of the concrete core. As the strength and lateral deformation of concrete core increases, it laterally expands to push out the confining steel. At the same time, the lateral compressive stress of concrete, \( f_l \), occurs in the spiral until yielding. The lateral pressure can be calculated from the mechanical equations as shown in Figure 1.

The lateral stress of concrete confined by lateral reinforcement depicted in Fig. 1 can be written as follows:

\[
\sigma_{l} = \frac{2A_s f_{yh}}{b_c s} \tag{1}
\]

where \( A_s \) = cross-sectional area of spiral; \( f_{yh} \) = yield strength of spiral; \( b_c \) = diameter of concrete core; \( s \) = spacing of spiral. From Equation (1), it can be seen that the strength gain of confined concrete depending on the lateral pressure, \( f_l \). It is assumed that the lateral stress of the steel attains the yield stress \( f_{yh} \) when the maximum load is reached. Actually, this assumption is not valid. The lateral confining stress \( f_l \) depends on the potential lateral expansion of plain concrete. The lateral strain nonlinearly increases as the increase of the axial stress. The increase will be much less when HSC is used (Ahmad and Shah [2]). Hence, the assumption that lateral reinforcement will be yielding when the peak load is attained is not the same with the actual condition. In fact, in accordance with the experimental data of HSC columns (Ahmad and Shah [2]; Martinez et al. [3]), the stress in the spiral at the peak load is frequently lower than the yield stress.

2.2. Square Columns

Essentially, it has been well known that spiral provides better confining effect than rectilinear hoops and ties (Sheikh and Uzumeri [4]; Yong et al. [5]). The confining mechanism of circular hoops or spiral occurred along the inner side of the hoops in contact with the concrete core, while for square hoops, the mechanism is more complicated. This is because the most effective portion being confined is mostly occurred at the four corners of the ties (see Fig. 2). The effective confined area of square columns will be greater if more hooks from the ties are applied to the longitudinal bars (Mander, et al. [6]). Figure 2 illustrates passive confining pressure that developed in square columns with different reinforcement arrangements. The confinement model proposed by Saatcioglu and Razvi [7] is based on the computation of equivalent uniform pressure that gives the same effect as the nonuniform confinement pressures as shown in Fig. 2. According to Razvi and Saatcioglu [1], the equivalent
uniform pressure $f_{uc}$ can be determined by reducing the average pressure with coefficient $k_2$. Thus, it can be written that the equivalent lateral confining stress as:

$$f_{lc} = k_2 f$$

where

$$k_2 = 0.15 \left( \frac{b_s}{s} \right) \left( \frac{b_s}{s} \right) \leq 1.0$$

Several previous studies have indicated that HSC columns provide less ductility and require higher confining effectiveness (Fafitis and Shah [8]; Yong, et al. [5]; Sheikh et al. [9]). However, Muguruma and Watanabe [10] state that although the confinement steel is not always yielding at the peak stress, the use of high-strength steel as transverse reinforcement can still improve the ductility of the columns significantly.

3. CONSTITUTIVE MODELS FOR CONFINED CONCRETE

The constitutive model for concrete plays an important role in the analysis and design of concrete structures. The frequently cited models to predict the peak stress and ductility or the stress-strain curve of confined concrete are introduced in this section.

Several existing empirical models by Nagashima, Sugano, Kimura, and Ichikawa (NSKI) [11], Muguruma, Nishiyama, and Watanabe (MNW) [12], Razvi and Saatcioglu (RS) [1], and Legeron and Paultre (LP) [13] were used to predict the present experimental stress-strain curve of the confined high-strength concrete with high-strength transverse steel.

Nagashima et al. [11] proposed a model base on the results of square column tests. The effectively confined core area concept, suggested by Sheikh and Uzumeri [4] was adopted in calculating confined concrete strength. The concept reflects the effects of longitudinal reinforcement and tie spacing. The model is applicable to columns with high-strength concretes. The stress-strain relationship consists of three parts. The expression proposed by Popovics [14] and used by Mander et al. [6] was adopted for the first part (ascending branch). The second part of the curve (descending branch) is a straight line, starting at the peak and terminating when the stress reaches 30% of the peak stress. A horizontal line is assumed beyond this point to form the third part, with constant concrete stress.

Muguruma et al. [12] modified their original model for the fourth time in 1993. The modification was based on the same earlier tests that formed the basis for the previous two modifications (Muguruma and Watanabe [10], and Muguruma et al. [15]). The original model was developed by Muguruma et al. [16]. The model is applicable to columns with normal and high-strength concretes, in the range of 20 to 130 MPa, confined with normal and high-strength steel. Based on their experimental work,
Muguruma et al. [12] proposed a three-part stress-strain curve which can be applied to concrete with a wide range of compressive strength confined by low and high yield strength transverse reinforcement. The first part of the curve consists of the commonly used second degree parabola that terminates and has a zero slope at the point \((f'_{cc}, \varepsilon_{cc})\). This part of the curve is the same as for unconfined concrete.

The second part of the curve consists of another second degree parabola with the origin redefined at the point \((f'_{cc}, \varepsilon_{cc})\) and terminates with a zero slope at the point \((f'_{cc}, \varepsilon_{cc})\), which is the peak of the confined concrete stress-strain curve. The third part of the curve is a straight line falling branch. The falling branch terminates when the average stress in the stress-strain curve reached the maximum for confined concrete.

Razvi and Saatcioglu [1] developed a stress-strain model for confined high-strength concrete based on their tests conducted on a large number of near-full size circular and square column specimens. The concrete strength considered in the experimental program ranged from 60 to 124 MPa and the yield strength of confinement steel ranged between 400 to 1000 MPa. It incorporates all the relevant parameters of confinement that have been observed to play important roles in column tests. These parameters include the type, volumetric ratio, spacing, yield strength, and arrangement of transverse reinforcement as well as concrete strength and section geometry. Therefore, it can be used for concrete confined by spirals, rectilinear hoops, crossties, welded wire fabric, and combinations of these reinforcements.

Recently, Legeron and Paultre [13] proposed a confinement model for HSC based on strain compatibility and transverse force equilibrium. This new approach is capable of predicting the effectiveness of transverse reinforcement, which is an important key in modeling the behavior of high-strength concrete confined with high-yield-strength steel. The stress-strain relationship is basically the same as that proposed by Cusson and Paultre [17], but the parameters of the model were recalibrated on the basis of large number of test data collected by the authors.

4. PROPOSED EMPIRICAL MODEL FOR CONFINED CONCRETE

As discussed previously, the stress-strain curve of concrete confined by high-yield-strength reinforcement depends extensively on the lateral confining stress and the core concrete strength. The shape of the stress-strain curve suggests that it can be modeled by three equations, one for the ascending part and another for the descending part is a straight line, starting at the peak and terminating when the stress reaches 30% of the peak stress. A horizontal line is assumed beyond this point to form the third part, with constant concrete stress.

4.1. Stress-Strain Relation

The ascending branch of the stress-strain curve of confined concrete has been investigated extensively by many researchers. One popular model that was developed by Mander et al. [6] seems to represent the available experimental data closely. This model, which is applicable in this study for strain up to \(\varepsilon_{cc}\), is based on the following expression (Popovics [14]):

\[
\text{Ascending branch:} \quad f_c = f'_{cc} \left( \frac{Xr}{r-1+X} \right) \quad (4)
\]

\[
\text{Descending branch:} \quad f_c = f'_{cc} \left[ 1 - 0.85 \left( \frac{\varepsilon_c - \varepsilon_{cc}}{\varepsilon_{cc85} - \varepsilon_{cc}} \right) \right] \geq 0.3 f'_{cc} \quad (5)
\]
where the variable \( f_c \) is the stress in the confined concrete at a strain equal to \( \varepsilon_c \). The parameter \( r \) is the function of the modulus of elasticity and coordinates of the peak on the stress-strain relationship for confined concrete, and is given by

\[
r = \frac{E_c \varepsilon_{cc}}{E_r \varepsilon_r - f'_{cc}}
\]  

(6)

where \( E_c \) is the modulus of elasticity of unconfined concrete. The following expression, originally proposed by Carasllquillo et al. [18] is found to produce good agreement with experimentally obtained values.

\[
E_c = 3320 \sqrt{f'_{cc}} + 6900
\]  

(7)

\( X \) in Eq. (8) is the ratio of strain \( \varepsilon_c \) to the strain \( \varepsilon_{cc} \) at peak confined concrete stress \( f'_{cc} \), expressed as:

\[
X = \frac{\varepsilon_c}{\varepsilon_{cc}}
\]  

(8)

In the proposed model, expressed by Eqs. (4) and (5), factors for controlling the stress-strain relation of confined concrete are the peak stress, the strain at the peak stress and the strain corresponding to 85% of the peak stress \( f'_{cc} \) of the falling branch. The effect of confinement on these three parameters was determined based on the test results, as described next.

To predict the peak stress and the corresponding strain, the following formulations are utilized;

\[
f_{cc} = f_{co} + \Delta f_c
\]  

(9)

and

\[
\varepsilon_{cc} = \varepsilon_{co} + \Delta \varepsilon_c
\]  

(10)

where; \( f_{co} \) and \( \varepsilon_{co} \), are the peak stress and strain of the unconfined concrete, and \( \Delta f_c \) and \( \Delta \varepsilon_c \), are the enhancements in concrete strength and the corresponding strain due to lateral confinement, respectively.

Table 1. Experimental work included in the analysis

<table>
<thead>
<tr>
<th>Reference</th>
<th>Researcher</th>
<th>Number</th>
<th>Shape</th>
<th>Cross section (mm)</th>
<th>Compressive strength (MPa)</th>
<th>Volumetric ratio (%)</th>
<th>Yield strength (MPa)</th>
<th>Longitudinal steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Nagashima et al. (1992)</td>
<td>20</td>
<td>Square</td>
<td>225</td>
<td>60 - 118</td>
<td>1.66 - 4.32</td>
<td>807 - 1,387</td>
<td>8 - 12 bars</td>
</tr>
<tr>
<td>19</td>
<td>Nishiyama et al. (1993)</td>
<td>8</td>
<td>Square</td>
<td>250</td>
<td>108.7</td>
<td>1.79 - 4.06</td>
<td>813 - 840</td>
<td>12 bars</td>
</tr>
<tr>
<td>20</td>
<td>Cusson and Paultre (1994)</td>
<td>10</td>
<td>Square</td>
<td>235</td>
<td>52 - 116</td>
<td>2.80 - 4.90</td>
<td>680 - 770</td>
<td>4 -12 bars</td>
</tr>
<tr>
<td>21</td>
<td>Li et al. (2001)</td>
<td>8</td>
<td>Square</td>
<td>240</td>
<td>52 - 82.5</td>
<td>2.00 - 5.00</td>
<td>1,318</td>
<td>8 bars</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>Circular</td>
<td>240</td>
<td>52 - 82.5</td>
<td>1.17 - 2.94</td>
<td>1,318</td>
<td>6 bars</td>
</tr>
<tr>
<td>22</td>
<td>Issa and Tobaa (1994)</td>
<td>4</td>
<td>Square</td>
<td>125</td>
<td>82.7</td>
<td>1.43 - 3.57</td>
<td>586</td>
<td>none</td>
</tr>
<tr>
<td>23</td>
<td>Saatcioglu and Razvi (1998)</td>
<td>11</td>
<td>Square</td>
<td>250</td>
<td>60 - 124</td>
<td>1.32 - 2.17</td>
<td>570 - 1,000</td>
<td>8 - 12 bars</td>
</tr>
<tr>
<td>24</td>
<td>Razvi and Saatcioglu (1999)</td>
<td>10</td>
<td>Circular</td>
<td>250</td>
<td>60 - 124</td>
<td>0.41 - 1.32</td>
<td>660 - 1,000</td>
<td>8 bars</td>
</tr>
<tr>
<td>25</td>
<td>Assa et al. (2001)</td>
<td>15</td>
<td>Circular</td>
<td>145</td>
<td>50 - 90</td>
<td>1.18 - 4.34</td>
<td>909 - 1,296</td>
<td>none</td>
</tr>
<tr>
<td>26</td>
<td>Hong and Han (2005)</td>
<td>10</td>
<td>Circular</td>
<td>250</td>
<td>84.8 - 128</td>
<td>0.32 - 1.92</td>
<td>1,026 - 1,288</td>
<td>none</td>
</tr>
</tbody>
</table>

The parameters primarily influencing the stress-strain relationship of confined concrete include the strength of concrete, yield strength of the confining reinforcement, volumetric ratio of the confining reinforcement to the concrete core as well as spacing between confining reinforcement, dimensions of the column, and the configuration of the lateral confining reinforcement. All these parameters are considered in the presented model. Table 1 presents the experimental work used in the analysis including 102 concrete specimens with different cross section, compressive strength, yield strength and volumetric ratio of the transverse reinforcements.
4.2. Formulation of Confinement Effect

In this study, the effective confinement index was defined as the effective lateral pressure \( p_e \) calculated from Eq. (11).

\[
p_e = k_{s} k_{c} \rho_{s} f_{s,c}
\]

(11)

where \( k_{s} \) is the ratio that relates the average lateral pressure to confined concrete strength. The following expression was suggested for \( k_{s} \).

\[
k_{s} = 6.7 (f_{s,c})^{0.17}
\]

(12)

\[
f_{s,c} = k_{s} \rho_{s} f_{s,c}
\]

(13)

where \( f_{s,c} \) is the equivalent lateral pressure that produces the same effect as uniformly applied pressure; \( \rho_{s} \) is the volumetric ratio of transverse reinforcement, defined as volume of transverse steel divided by volume of concrete core; \( f_{s,c} \) is the stress in the transverse reinforcement at the peak concrete strength (see next section); and \( k_{c} \) is the effective confinement coefficient (Mander et al. [6]) given by

\[
k_{c} = \left( \frac{1 - \sum_{i=1}^{n} (w_{i}')}{6b'd_{c}} \right) \left( 1 - \frac{s'}{2b_{c}} \right) \left( 1 - \frac{s'}{2d_{c}} \right) \left( 1 - \rho_{c} \right)
\]

(14)

for square cross sections, and

\[
k_{c} = \left( \frac{1 - s'}{2b_{c}} \right) \left( 1 - \rho_{c} \right)
\]

(15)

for circular cross sections,

where \( w_{i}' \) is the clear spacing between adjacent longitudinal steel bars in a rectangular section; \( s' \) is the clear spacing of ties; \( b_{c} \) and \( d_{c} \) are the widths of the concrete core; and \( \rho_{c} \) is the longitudinal reinforcement ratio in the core section.

A regression analysis was performed on all available experimental results to formulate the peak strength \( f_{c} \) in terms of \( p_e \).

\[
\frac{f_{c}}{f_{c}^p} = 1.0 + 0.626 \left( \frac{p_{e}}{f_{c}^p} \right)
\]

(16)

The confinement effects according to each variable were analyzed by calculating and comparing the loads carried by the core concrete. The parametrical study was proceeded by measuring the strength enhancement factor defined as

\[
K_{s} = \frac{f_{c}^p}{0.85 f_{c}'}
\]

(17)

4.3. Ductility of Confined Concrete

It is well known that the strength and ductility of concrete are inversely proportional. Ductility of confined concrete is indicated by the slope of the descending branch of the stress-strain relationship. The slope of the descending branch is a function of two strain values in the analytical model developed in this investigation. These values include strains corresponding to the peak stress \( \varepsilon_{c,c} \), and 85% of the peak within the descending branch of the stress-strain relationship \( \varepsilon_{c,85} \). The effects of concrete strength and lateral steel strength on ductility of confined concrete were subsequently
introduced using coefficients $k_1$ and $k_2$ proposed by Razvi and Saatcioglu [1] are used in the equations, considering the application.

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1.0 + 3.63 (k_1 K)^{0.6}$$  \hspace{1cm} (18)

where

$$K = k_1 \frac{\rho_s f_{sc}}{f_{co}}$$  \hspace{1cm} (19)

$$\frac{\varepsilon_{cc,85}}{\varepsilon_{co}} = 1.0 + 23.79 \left( k_2 \frac{\rho_s f_{sc}}{f_{co}} \right)$$  \hspace{1cm} (20)

where

$$f_{sc}' = 0.85 f_s'$$  \hspace{1cm} (21)

$$\varepsilon_{co} = 0.0028 - 0.0008 k_3$$  \hspace{1cm} (22)

$$k_3 = \frac{40}{f_{co}} \leq 1.0$$  \hspace{1cm} (23)

Since it is very difficult to determine the unconfined concrete properties ($f_{sc}$, $\varepsilon_{co}$) through tests, $f_{sc}'$ and $\varepsilon_{co}$ specified in Eqs. (21)-(23) proposed by Razvi and Saatcioglu [1] are used in the equations.

To evaluate the effects of lateral reinforcement on the ductility of HSC cores, a dimensionless factor, $D_c$, is introduced. This factor is referred to as the ductility enhancement factor, and is defined as the ratio of the strain of confined concrete at 85 percent of the peak stress on the descending branch of the stress-strain curve to the unconfined cylinder strain at the peak.

4.4. **Stress in Transverse Reinforcement at Peak Concrete Strength**

In this section, the relationship between the lateral confining pressures is simplified. Formula for $f_{sc}$ (Eq. (24)) was derived from a regression analysis of the parameters related to the iterative procedure proposed by Hong and Han [26].

$$f_{sc} = E_s \left[ 0.45 \varepsilon_{co} + 0.73 \left( \frac{k_1 \rho_s f_{sc}'}{f_{co}} \right)^{0.70} \right] \leq f_{sc}'$$  \hspace{1cm} (24)

where $E_s$ is the modulus of elasticity of transverse reinforcement and $f_{sc}'$ is in MPa.

5. **COMPARATIVE STUDIES**

The modeling for confined concrete is required to precisely describe its ascending branch, peak value, and descending branch. The authors propose to establish a method based on three parameters, $f_{sc}'$, $\varepsilon_{co}$, and $\rho_s$. To evaluate the effects of lateral reinforcement on the ductility of HSC cores, a dimensionless factor, $D_c$, is introduced. This factor is referred to as the ductility enhancement factor, and is defined as the ratio of the strain of confined concrete at 85 percent of the peak stress on the descending branch of the stress-strain curve to the unconfined cylinder strain at the peak.
\( \varepsilon_{cc} \) and \( \varepsilon_{cc85} \), which are taken to represent the whole stress-strain curve. Table 2 illustrates the statistics obtained for the three parameters, compares the available experimental results from 102 confined concrete columns tested by several researchers [11,19-26] with the predictions from the proposed confinement model and several selected confinement models. A comparative study was also performed on the performance of the models of 102 specimens tested by several researchers. Fig. 3 compares the strength enhancement factors \( f'_{cc}/f_{cc0} \), peak strain \( \varepsilon_{cc}/\varepsilon_{cc0} \), and ductility of confined concrete \( \varepsilon_{cc85}/\varepsilon_{cc} \), produce mean errors of 7, 26, and 33%, respectively, for the proposed model when compared with the experimental results.

It should be noted that all the four confinement models of the study are applicable to square sections whereas only two, namely Razvi and Saatcioglu’s model [1] and Legeron and Paultre’s model [13], can be applied to circular sections. It should be emphasized that the post-peak description of the stress-strain curve is of greater significance in order to ascertain the ductility and failure related aspects of concrete columns. Keeping this fact in mind, the study is also aimed to determine the strain values at one specified stress levels in descending portion, i.e., 85 percent of the peak stress. Most of the

![Figure 3. Comparison of the experimentally obtained strength and ductility enhancement factors with equations proposed by authors and other researchers: (a) Nagashima et al. [11], (b) Muguruma et al. [12], (c) Legeron and Paultre [13], (d) Razvi and Saatcioglu [1], and this study.]

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a) Specimen HL08LA by Nagashima et al. [11]

b) Specimen Unit 1 by Nishiyama et al. [19]

c) Specimen 5D by Cusson and Paultre [20]

d) Specimen 5HC by Li et al. [21]

e) Specimen B-4 by Issa and Tobaa [22]

f) Specimen CS-22 by Saatcioglu and Razvi [23]

g) Specimen 2HC1 by Li et al. [21]

h) Specimen CC-14 by Razvi and Saatcioglu [24]

Figure 4. Comparison of experimental and analytical curves for square and circular cross sections confined by high-yield-strength steel.
analytical stress-strain curves reported by researchers do not provide a formula to calculate the strain value at the stress of 85 percent of the peak stress. So, for these cases, no comparison is possible, except Razvi and Saatcioglu’s model. The uncertainty related to the predicted confined concrete strength was found to be relatively low for all models. The coefficient of variation is ranging from 10.4 to 26.4 percent (Table 2). It can also be seen that the uncertainty in the prediction of ductility $\varepsilon_{\text{d,55}}$ was found to be relatively high (Razvi and Saatcioglu’s model). On the other hand, Nagashima’s, Muguruma’s, and Razvi’s models underestimate $\varepsilon_{\text{d,55}}/\varepsilon_{\text{c,55}}$.

Fig. 4 compare the analytical stress-strain curves derived from the proposed model and several selected confinement models from other researchers with the available experimental stress-strain curves of selected specimens tested by several researchers [11,19-26]. It may be seen from these figures that the agreement between the analytical stress-strain curves from the proposed model and the available experimental stress-strain curves is satisfactory. In addition, the proposed model gives better predictions for different configuration compared to those given by other models.

6. CONCLUSIONS

An analytical stress-strain model for concrete confined by high-strength concrete with high-strength steel was developed, using a linear regression analysis involving a total of 102 test data used combination of high-strength concrete and steel. Four existing analytical models for high strength concrete confined by high-strength steel were studied, and statistical evaluation of three key parameters of the stress-strain curve was presented. The study indicated that all models predict the ascending branch of the stress-strain curve fairly well, whereas the predicted descending branch is not consistent. Finally, the results of predictions from the proposed model show a good agreement with the test results.

REFERENCES