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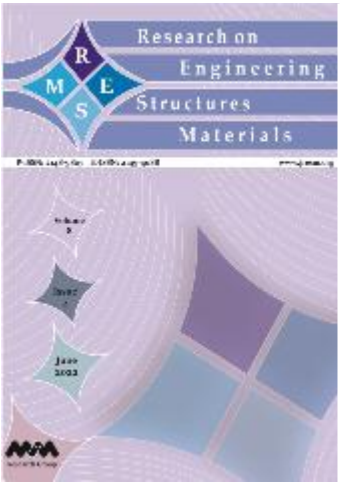

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Research Article

Experimental study on stress-strain characteristics of ultra high strength concrete and its effect on stress block parameters for flexural design of building

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Abstract

Flexural design of reinforced concrete members in structures such as buildings, bridges, etc. presented in various standards are based on the equivalent rectangular stress block and stress-block parameters for high strength concrete. However, with design of high strength concrete mixes these existing stress block parameters for normal and high strength concrete have become redundant and does not give a true representation of the obtained stress-strain curves for ultra-high strength concrete. The primary stress-strain characteristics affecting the stress block parameters are strain at peak stress, the ultimate strain and the shape of the rising limb of the curves. Past studies have confirmed a varying behaviour of all these characteristics in the stress strain curves at higher strength. The present study first evaluated the stress strain curves for high strength concrete from 90 to 140 MPa. The characteristics of the curves were coMPared with those of normal and high strength concrete. Based on the observed stress strain characteristics, the modified stress block parameters for the ultra-high strength concrete are presented. The proposed stress block was coMPared with the Indian standard IS456 and European design standard EC: 02-2004. The proposed stress block will be useful for the required modification and updating of various standards pertaining to the flexural design of ultra-high strength concrete with cylindrical compressive strength in from 90 to 140MPa.

1. Introduction

Various standards propose a stress block based flexural design methodology for concrete structures. This rectangular stress block is modified using the stress block parameters to give an accurate representation of the observed stress-strain behaviour of concrete. The actual stress strain curves for the concrete have a rising limb at peak and a falling limb. With appropriate choice of the stress block parameters these characteristics can be incorporated in the rectangular stress blocks. The use of the equivalent rectangular stress distribution was initially suggested by Emperger [1], which was refined by Whitney [2] for use in ultimate strength design, and then empirically confirmed by Hognestad et al, [3] and Mattock et al, [4]. Hognestad et al, [3] first introduced the rectangular stress block model based on experimental investigation on normal strength concrete. The rectangular stress block dimensions utilized in regular concrete members cannot be used for high and ultra-high strength concrete members safely, [5]. The applicability of ACI 318-95 rectangular stress block parameters to higher strength concretes was investigated by Attard and Stewart (1998) [6]. They demonstrated that the ultimate moment capacity for a rectangular section made of ductile single reinforcement is largely unaffected by the stress block model. Bernardo & Lopes [7] conducted an experimental investigation on the

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evolution of depth of neutral axis at failure with the ductility at bending on High Strength Concrete (HSC) beams. Different current RC design codes [8,9] have used equivalent rectangular concrete stress blocks that depend simply on the strength of concrete. It was discovered that, in coMParison to the experimental values, the theoretical formulations based on the usage of the concrete's rectangular block diagram to compute the depth of neutral axis at failure produced significantly smaller values. As a result, it was determined that the ACI 318-1989 rectangular stress block diagram was insufficient for HSC beams. According to Cetin and Carrasquillo [10], no one equation of different codes and previous research appears to accurately describe the flexural strength of HSC, and as a result, measured values should be used rather than hypothesized ones. Another crucial factor in the ultimate strength design is the ultimate concrete compressive strength. Although it is not necessary for the ultimate flexural strength of reinforced concrete cross sections, this variable has a noticeable iMPact on the final curvature. According to Mattock et al. [4], 0.003 is a fairly conservative estimate of the ultimate strain of concrete. Many design codes have also approved this value (NZS 3101 2006; ACI 318-08 2008; AS 3600 2009). According to Kahn et al. [11], the ultimate value of 0.003 is accurate up to 102 MPa for concrete and offered the best forecast of the ultimate moment. The limit of 0.003 for concrete under compression may be increased for higher strength concrete, according to Mansur et al ,[12] The final concrete strain results from Ibrahim and MacGregor (1996) were significantly higher than the limitation value of 0.003. However, they came to the conclusion that the value of 0.003 adopted by the ACI code seems suitable as a cautious lower bound of experimental results based on the reported values in prior testing of C-shaped specimens. The assumed stress strain behaviour and stress block parameters for the evaluation of flexural capacity of the beams as given in IS 456 [13] is presented in Figure 1. The strain at the peak stress is assumed to be 2500 microstrains and the peak strain as 3500 microstrains. Based on the assumed stress block the flexural capacity of the members are established. The stress block assumed in Eurocode EC 02: 2004 [14] is shown in Figure 2. The assumed stress-strain behaviour in Eurocode varies with the variation on the compressive strength of the concrete and therefore gives a more accurate representation of the actual stress-strain behaviour at different strength of concrete. These stress-strain characteristics and the resulting stress block parameters have underlying effect on the mechanical [15,16], fracture [17] and durability [18] properties of the concrete.

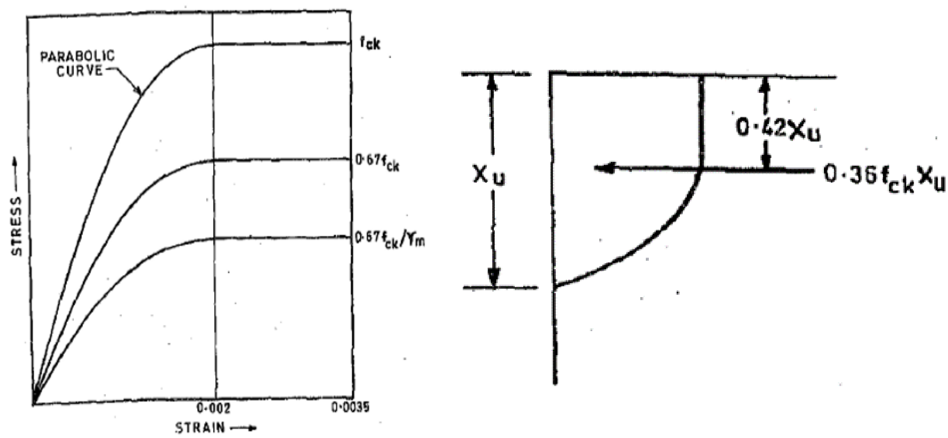
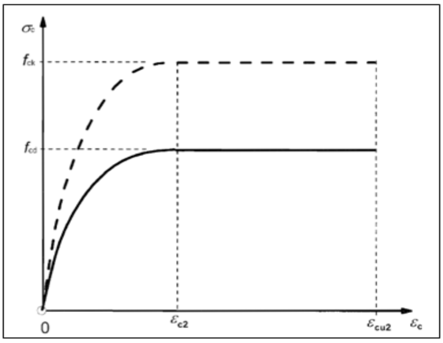


Fig. 1 Stress-Strain behaviour & Stress block parameters adopted in IS 456:2000 [13]



fck(Mpa)	Upto 50	55	60	70	80	90
εc2(%)	2	2.2	2.3	2.4	2.5	2.6
εcu2(%)	3.5	3.1	2.9	2.7	2.6	2.6

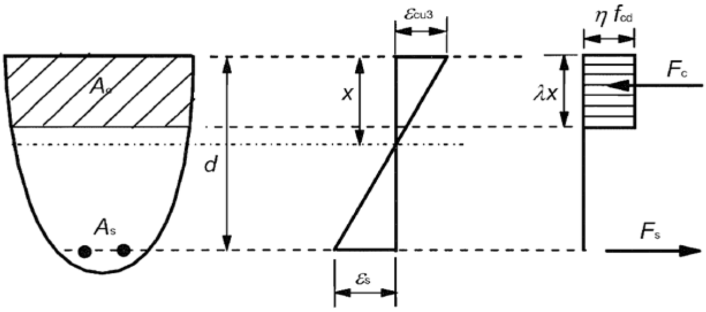


Fig. 2 Stress strain behaviour and stress block in Eurocode EC 02-2004 [14]

The primary aim of the present study is to calculate the stress block parameters "K' (strength reduction factor) and k_2 (factor for depth of resultant compressive force) using experimental strain measurements. The model proposed in European Design Standard EC: 02-2004 was examined in this study, and stress block parameters was converted into those utilised in the IS code design technique. The outcomes of the experiments were then coMPared to the design parameters.

2. Concrete Ingredients

In this study cementitious material with a broad range of particle size distribution were selected which leads to a higher packing density of concrete. The physical and chemical properties of cementitious material are given in Tables 1 & 2 respectively. Cementitious Materials used in the study are OPC53, GGBS, Flyash, ultrafine GGBS, and Silica fume conforming to IS 269[19], IS 16714[20], IS 3812[21], IS 16715[22], IS 15388[23] respectively. Nano-silica was also used to fill the pores of Nano-size. Similarly, to increase the packing density of solid materials, three different types of aggregates were used namely Quartz sand, Ground Quartz, and River sand. The properties of the materials are given in Table 1 and 2.

Table 1. Physical properties of materials

S. No.	Properties	Cement	G.G.B.S	Flyash	UFGGBS	Silica Fume	Nano Silica
1.	Fineness(m^2/kg)	323	400	310	2026	16701	24000
2.	Specific Gravity	3.15	2.93	2.28	2.88	2.28	2.21

Table 2. Chemical properties of materials

S. No.	Properties	Cement	G.G.B.S	Flyash	UFGGBS	Silica Fume
1	Loss of Ignition (LOI)	2.3	0.33	0.4	0.17	2.73
2	Silica (SiO_2)	20.71	34.41	60.95	33.05	85.03
3	Iron oxide (Fe_2O_3)	4.08	1.18	5.7	0.58	-
4	Aluminum oxide (Al_2O_3)	5.15	18.45	26.67	20.40	-
5	Calcium oxide (CaO)	59.96	36.46	2.08	33.14	-
6	Magnesium oxide (MgO)	4.57	7.00	0.69	7.62	-
7	Sulphate (SO_3)	1.84	0.097	0.29	0.19	-
8	Na_2O	0.42	0.30	0.06	0.19	0.73
9	K_2O	0.56	0.37	1.46	0.58	2.96
10	Chlorides	0.012	0.022	0.009	0.016	-

3. Mix Design Details

In the present study, the proportion of individual cementitious material was decided using the Modified Andreasen and Andersen equation [24,25,26]. From mixes that were mathematically optimized based on their Residual Sum of Squares (RSS) value using an excel solver, three final mixes were cast in the laboratory for a study on their Stress-strain behavior. The details of the mix composition of these optimized mixes are given in Table 3. The total cementitious content used is between 950 to 1000 kg/m^3. To attain better particle packing density, a combination of fine aggregates was used i.e., Ground quartz, Fine quartz sand, and coarse quartz sand. The nano-silica was used as 3% replacement for OPC content.

Table 3. Mix Proportion for the experimental study

Mix ID	Mix 1	Mix 2	Mix 3
w/binder	0.17	0.17	0.17
Cement	597	707	636
Flyash	85	42	95
GGBS	165	0	110
Silica fume	135	180	139
Nano Silica	18	21	20
Admixture (%)	1	1	1
FQS	922	734	922
GQ	256	0	256
CQS	0	534	0
Total binder content (kg/m^3)	1000	950	1000

4. Stress-strain Study on Ultra-High Strength Concrete

Concrete samples were tested in a strain-controlled, closed-loop servo hydraulic compression testing system with 3000kN capacity in order to determine the stress strain properties of the high strength concrete. In order to measure strain, a compress meter and a Linear Variable Displacement Transducers (LVDT) were placed at the halfway point of the height (Figure-3). CoMPared with normal strength and high strength Concrete, the effect of specimen geometry on the compressive strength is very small for ultra-high strength concrete. For recording the strain, LVDT and compress meter were utilized based on the recording channels available in the strain-controlled machine. The LVDT and compress meter readings are reported in the study. Generally, the LVDT is suitable for capturing complete stress strain response but accuracy is not at par with compress meter due to error coming from platen-to-platen measurement and larger gauge length. For the compression test, a slow rate of loading in the range of 0.4 μm/sec was used in order to get a complete stress-strain curve. Normal strength concrete fails gradually after attaining its peak load, but high strength and ultra-high strength concrete bursts upon reaching their peak loads [27, 28, 29, 30,34,35]. The recorded stress strain curves are shown in Figure-4 to Figure-6. In the Figures for each specimen the peak stress and the strain at peak stress are given in the legend for each sample.

Fig. 3 Testing setup for Stress Strain Curve determination

The strain at peak stress and the ultimate strain at failure for the specimen are recorded and are shown in the Figure 3 to Figure 5. As depicted in the stress strain plots for ultra-high strength concrete the strain at peak stress and the ultimate strain at failure coincides. The stress strain curves for the concrete above 90MPa compressive strength depicts a straight-line path for the rising limb. Also, the post peak behaviour is negligible leading to equal values for the strain at peak stress and the ultimate strain at failure. Also, the stress-strain curves for the LVDT shows a higher strain value as coMPared to the compress meter values. The reason can be attributed to the difference in gauge length ratios adopted for the compress meter and Linear Variable Displacement Transducer (LVDT). From the curve, one can conclude that specimen with smaller gage length ratio show more ductility than that of larger ratio. This was because the measurement using larger gage ratio can detect more cracks processed within the gage length region during loading stage. The platen-to-platen axial measurements were widely used, especially in ultra-high strength concrete because the test technique was able to capture all cracks within the specimen tested. In ultra-high strength concrete, sudden spalling of concrete cylinder surface makes it difficult to get a post peak behavior [31,32,33]. Thus, the platen-to-platen measurements include extra deformation from the weak contact between loading plate and specimen, consequently the stress-strain curves become more brittle. It was concluded that strain values measured in the stress-strain curve are strongly dependent on the gage length ratio used in compression test. Deformations measured from specimen surface give strain values of stress-strain curve. After peak load, concrete begins to spall and disturb strain measurement in specimen. However, deformations from platen to platen give stable behavior. This makes platen to platen strain measurements popular. Based on the observed stress strain behaviour stress block parameters were derived and discussed in section-5.

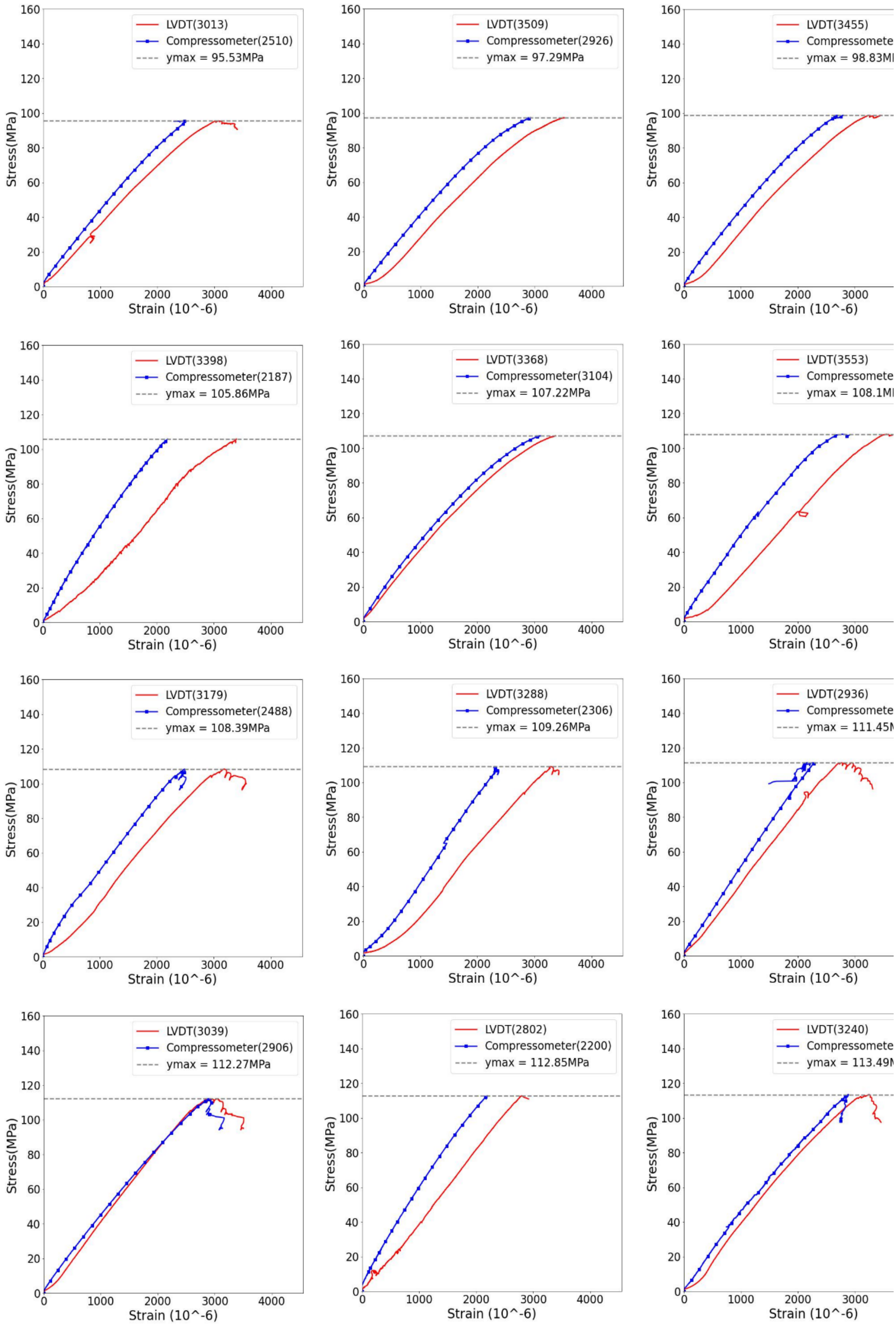


Fig. 4 Stress strain characteristics of Concrete (Compressive strength between 95 MPa to 113 MPa)

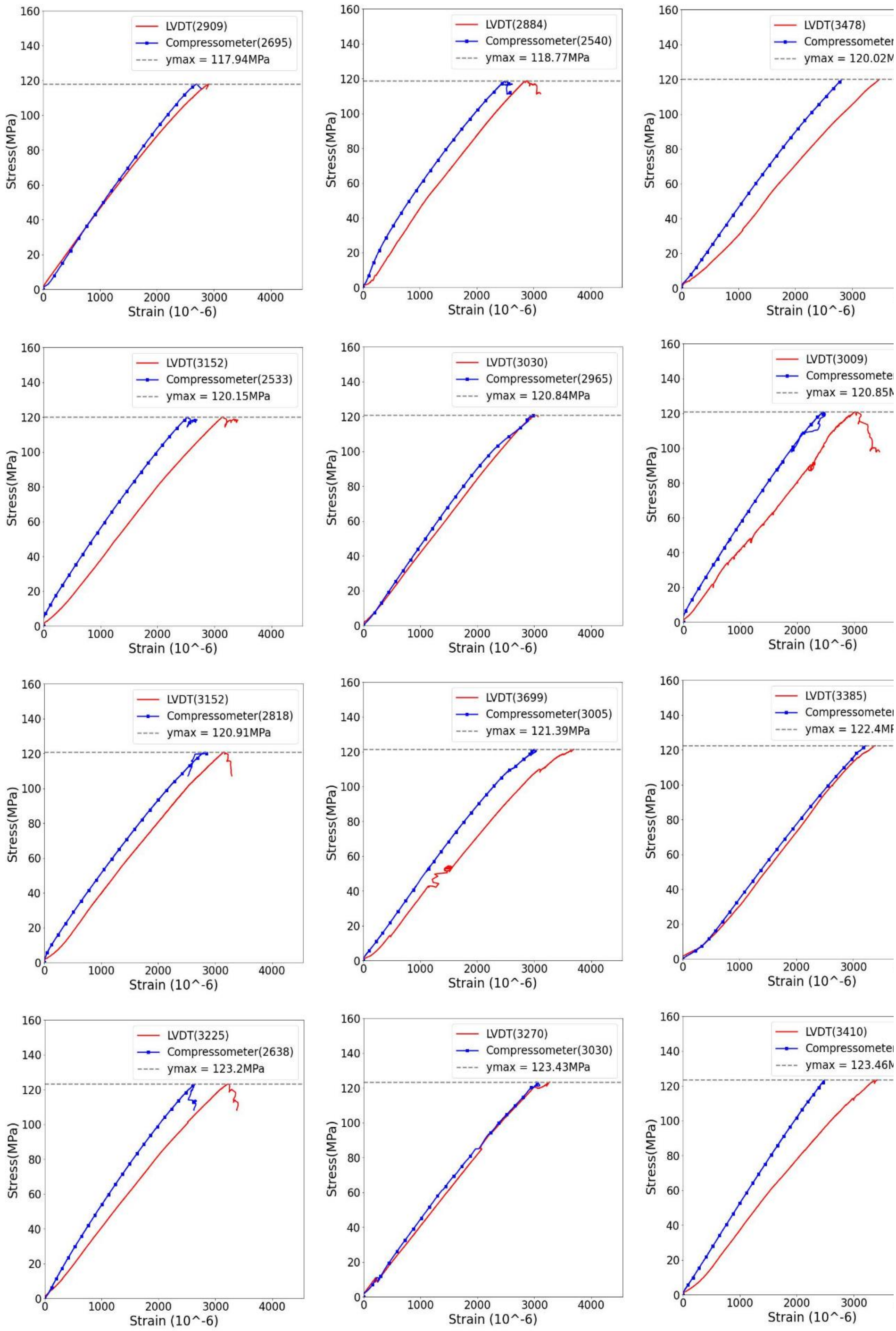


Fig. 5 Stress strain characteristics of Concrete (Compressive strength between 113 MPa to 123 MPa)

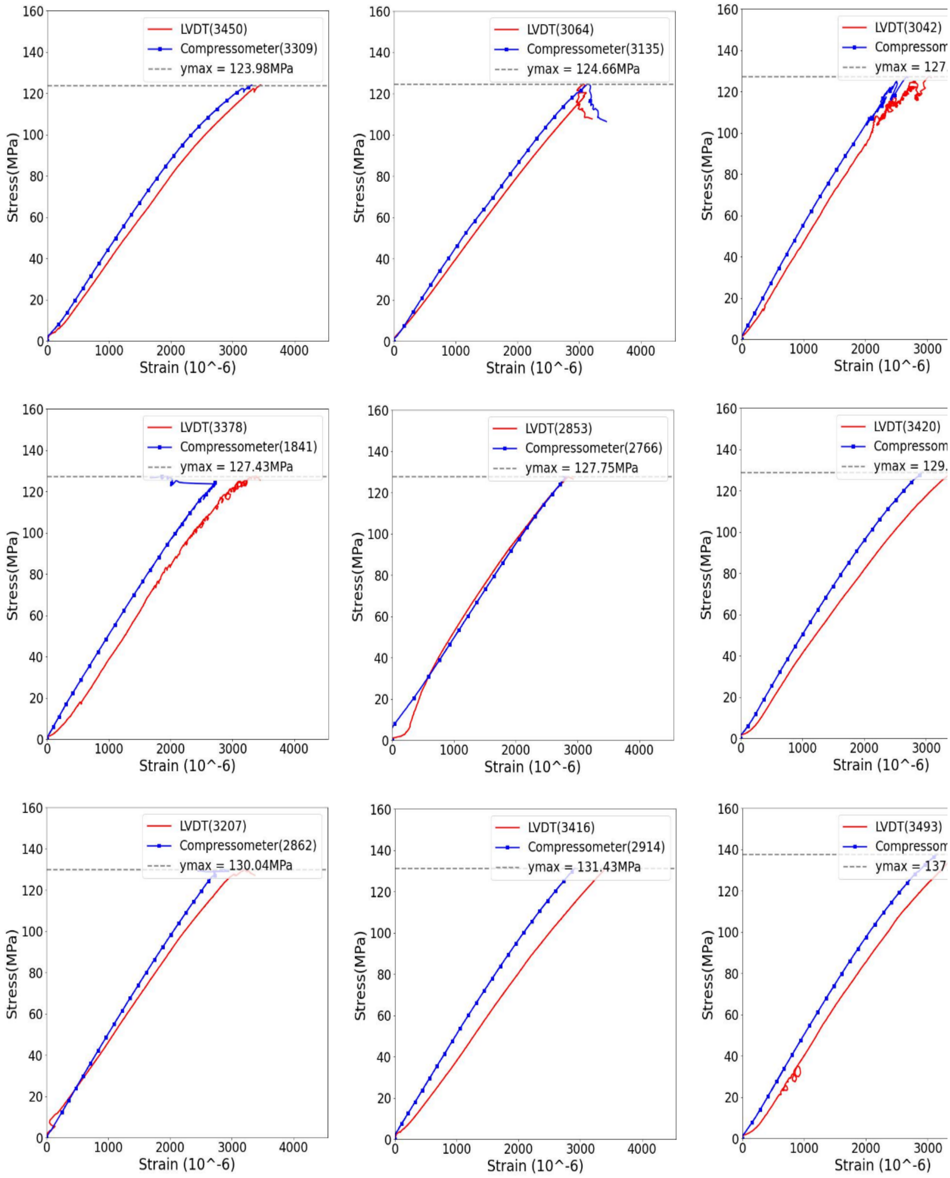


Fig. 6 Stress strain characteristics of Concrete (Compressive strength between 123 MPa to 138 MPa)

5. Determination of Stress-block Parameters and Moment Capacity from Experimentally Obtained Strain Values Using IS: 456 and Eurocode

As presented in past studies the total compressive force and its line of action from the extreme compression fiber can be expressed in terms of three stress block parameters k1, k2, and k3. k1 is known as shape factor and is defined as the factor for converting the area of rectangular stress into the assumed shape stress block based on stress strain behaviour. Mathematically it can be evaluated using Equation (1).

$$k1 = \frac{Area\ of\ actual\ stress\ block}{Area\ of\ rectangular\ stress\ block\ envalope} \quad (1)$$

The second stress block parameter k2 is related to the evaluation of location of the resultant compressive force of the stress block. Mathematically it is the ratio of the depth of resultant compressive force to depth of neutral axis. Equation (2) gives the mathematical formulation for stress block parameter k2.

$$k2 = \frac{\begin{matrix} Depth\ of\ Centroid\ of\ Assumed\ stress\ block \\ from\ extreme\ compression\ fiber \end{matrix}}{Depth\ of\ Neutral\ Axis} \quad (2)$$

The third stress block parameter k3 is a factor for consideration of stress reduction and reduces the maximum ordinate of stress block. Parameter k3 is evaluated as product of two factors – (i) factor of consideration of long-term effect including the way load is applied (αcc), and (ii) factor for conversion of conversion of cube to cylinder strength. Equation (3) and (4) presents the mathematical formulation and implication of the stress block parameter k3.

$$k3 = \alpha_{cc}\ \mathrm{x}\ \mathrm{S1} \quad (3)$$

$$ordinate\ of\ stress\ block = \frac{k3 * f_{ck}}{\Upsilon_{mc}} \quad (4)$$

Based on literature, the value for αcc in Equation (2) was taken as 0.85. In Equation (4) fck is the characteristic compressive strength of concrete and Ymc is the partial factor of safety of concrete. According to Indian standard code of concrete IS 456:2000, Ymc was taken as 1.5 in the present study.

For simplification, the two stress block parameters k1 and k3 can be combined to single stress block parameters as stated in equation (5):

$$K = \frac{k1 * k3}{\Upsilon_{mc}} \quad (5)$$

Also, the stress block parameters can be presented in terms of two factors r1 and r2 which represents the strain at peak stress (εc) and ultimate strain at failure (εcu). These two factors are mathematically presented in Equations (6) and (7):

$$r1 = \frac{\varepsilon_c}{\varepsilon_{cu}} \quad (6)$$

$$r2 = \frac{\varepsilon_{cu} - \varepsilon_c}{\varepsilon_{cu}} \quad (7)$$

These stress block parameters and the factors are primarily depended on the following stress strain characteristics of a particular concrete type:

Shape of the rising limb of the stress-strain curve: The stress strain behaviour of normal strength concrete (upto 50 MPa) shows a parabolic rising limb (Figure-4). This has been widely adopted by standard codal provisions around the world. But with increase in strength of the concrete the behaviour of the rising limb changes significantly. As presented by Singh et al. [20] the rising limb of the stress-strain curve for high strength concrete assumes a straight-line path. In the present study for the concrete strength above 90 MPa the rising limb depicts a nearly perfect straight line with only a little deviation.

Strain at peak stress, Ultimate Strain at failure and their difference: For normal strength concrete, up to 55 MPa, Indian standard code assumes a constant value of 2000 micro strains and 3500 micro strains as the strain at peak stress and ultimate strain respectively. With increase in strength concrete, these values also vary significantly leading to variation in the stress block and stress block parameters. As reported by Singh et al, [20] with increase in the compressive strength of the concrete the difference between these two strain values shrinks and ultimately gets vanished. As observed in the experimental investigation of concrete cylinders above 90MPa strength, there exist no much difference between the strain value at peak stress and the ultimate strain. The change leads to removal of upper rectangular portion of the assumed stress block in IS 456:2000. The variation in the stress block with changes in stress-strain characteristics due to increase in compressive strength is shown in Figure 7. The Figure 7A shows a rectangular stress block which will be modified using the stress block parameters based on the stress strain characteristics. Figure 7B is a typical stress block parameter with parabolic and rectangular portion. The parabolic stress block seems to be a good representation of actual stress-strain curve up to 55 MPa compressive strength. With increase in the compressive strength the parabolic portion becomes linear as show in Figure 7C. This gives a triangular stress block with rectangular upper part. This stress block gives satisfactorily representation of stress-strain behaviour up to 90 MPa. Above 90 MPa the upper rectangular portion shrinks and ultimately dies out giving a stress block as presented in Figure 7D. Based on these shapes of stress blocks the parameters and factors can be evaluated for the flexural design of concrete structures with different concrete compressive strength.

Table 4 shows the calculated stress block parameters for different strength range of concrete. The equations for calculating these parameters are given above as Equation (1) to (7). The stress block parameters k_1 and k_2 can be represented in terms of factor r_1 and r_2. The calculation of the stress block parameter for concrete above 90 MPa strength can also be done by adopting $r_1=1$, and $r_2=0$ in the stress block parameters for the 55 MPa to 90MPa concrete.

Table 4. Stress-block parameters for different strength of concrete

Upto 55 MPa (Fig 7B)	55 MPa to 90 MPa (Fig 7C)	Above 90 MPa (Fig 7D)
$k1 = \frac{2}{3}r1 + r2$	$k1 = \frac{1}{2}r1 + r2$	$k1 = \frac{1}{2}$
$k2 = [\frac{2}{3}r1\left(r2 + \frac{3}{8}r1\right) + r2(\frac{r2}{2})]/k1$	$k2 = [\frac{1}{2}r1\left(r2 + \frac{1}{3}r1\right) + r2(\frac{r2}{2})]/k1$	$k2 = \frac{1}{3}$
$k3 = \alpha_{cc} * S1$	$k3 = \alpha_{cc} * S1$	$k3 = \alpha_{cc} * S1$

Based on the evaluated stress block parameters the total compressive force and its line of action can be calculated for the flexural design of reinforced concrete structures. The total compressive strength in terms of stress block can be evaluated using equation (8) as follows:

$$C_u = width\ of\ beam * area\ of\ actual\ stress\ block$$

$$= b * k1 * area\ of\ rectangular\ stress\ block = b * k1 * k3 * \left(\frac{fck}{\Upsilon_{mc}}\right) * x_u$$

$$= K * fck * b * x_u \qquad \left\{K = k3 * \frac{fck}{\Upsilon_{mc}}\right\} \tag{8}$$

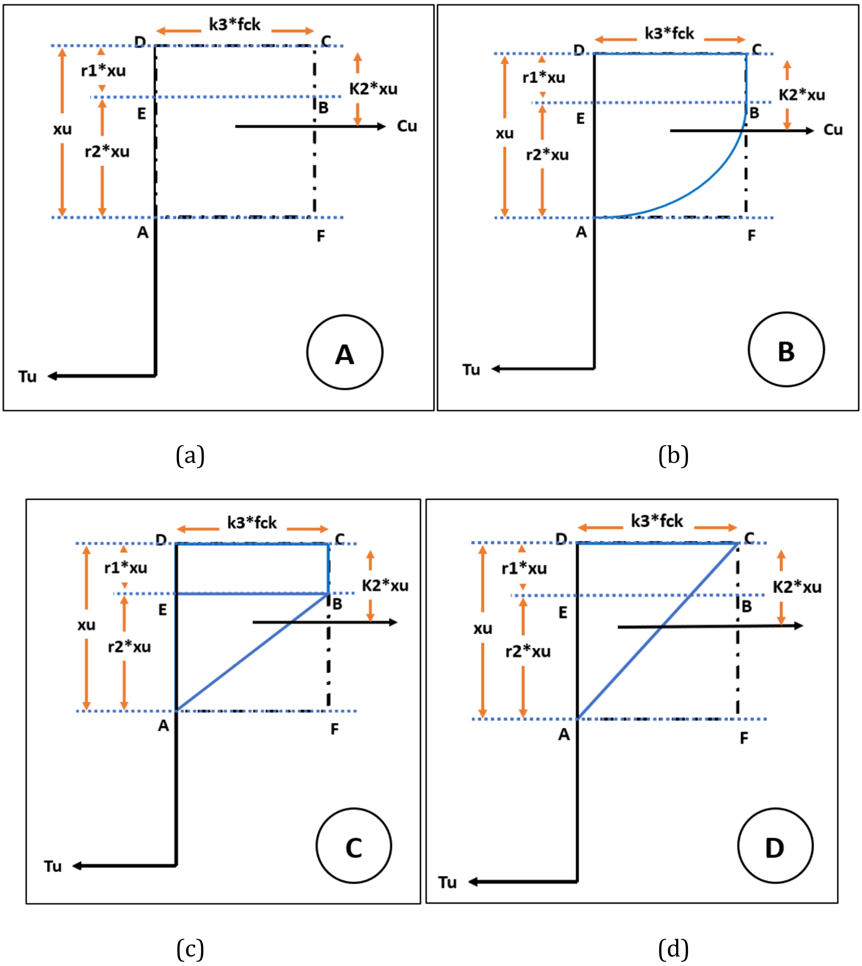


Fig. 7 (a) Rectangular stress-block, (b) Parabolic stress block (55MPa), Triangular stress-block (55MPa to 90 MPa), (d) Triangular stress block (above 90 MPa)

Calculation of neutral axis for balanced section (x_u) can be made using equation (9) as follows:

$$\frac{x_u}{d} = \frac{\frac{fy}{\Upsilon_s} * A_{st}}{K * fck * b * d} = \frac{\varepsilon_c}{\varepsilon_c + \varepsilon_{su}} \tag{9}$$

In equation 9, d represents the depth of the centroid of the tension reinforcement from the extreme compression fiber of the concrete (effective depth), fy is the yield strength of the reinforcement, Ast is the area of tension reinforcement, ϒs is the partial factor of safety for steel (=1.15 as per IS456-2000), and εsu is the ultimate strain in tension steel (= 0.002+0.87*(fy/E_s(modulus of elasticity of steel)).

The lever arm for calculation of moment capacity can be made using equation (10) as follows:

$$l = \ Lever\ arm\ = d - (k2 * x_u) \tag{10}$$

And the corresponding Moment capacity can be calculated using equation (11) as follows:

$$M_u = \ C_u * l \tag{11}$$

$$M_u = \ T_u * l \qquad \{T_u = \frac{fy * Ast}{\Upsilon_s}\} \tag{12}$$

Euro-code give a slightly different approach for evaluation of flexural capacity of reinforced concrete than IS 456:2000. The total compressive force in Eurocode is evaluated using equation (13) as given below:

$$C_u = \lambda * \eta * fcd * b * x_u \tag{13}$$

In equation 13, λ defines the effective height of the compression zone, η defines the effective strength, and fcd represents design compressive strength of the concrete. f_{cd} is given as follow in equation (14).

$$fcd = \alpha_{cc} * \frac{S1}{\Upsilon_{cc}} \tag{14}$$

The IS code equivalent of 13 has been suggested by Singh et al. [20] and is given in equation (15):

$$C_u = K' * fck * b * x_u \qquad \left\{K' = \ \lambda * \eta * \alpha_{cc} * \frac{S1}{\Upsilon_{cc}}\ and\ \ \lambda = 2 * k2\right\} \tag{15}$$

The depth of neutral axis can be calculated as per euro-code using equation (16) as given below:

$$\frac{x_u}{d} = \frac{1 - 0.44}{k4}\ , if\ cylinderical\ strength < 50MPa \tag{16}$$

$$\frac{x_u}{d} = \frac{1 - 0.54}{k4}\ , if\ cylinderical\ strength > 50MPa \tag{17}$$

$$k4 = 1.25 * (0.6 + \left(0.0014 * \frac{1000000}{\varepsilon_{cu}}\right)) \tag{18}$$

Moment capacity for balanced section as per Eurocode is given using equation (19) as given below:

$$Mu = C_u * (d - k2 * x_u) = \ C_u * \left(d - \frac{\lambda}{2} * x_u\right) \tag{19}$$

Using equation 11 and equation 19, moment capacities as per IS code and Euro code respectively for a beam of 200mm wide (b = 200mm), 400 mm deep (D = 400 mm) with clear cover of 25 mm is evaluated. Table 5 presents Moment calculation based on Modified IS code and Modified Eurocode methods.

6. Recommended Modifications in Codal Provisions for Incorporation of Ultra High Strength Concrete

Based on the findings of the present study following changes can be made to incorporate the design of ultra-high strength concrete structures:

- Modifications in the strain at peak stress and ultimate strain:

Eurocode EC02-2004 gives equations for evaluating the strength based strain values for concrete upto with compressive strength above 50MPa. The equations for strain at yield strain and the ultimate strain merges at 2600 microstrains. The equations from the Eurocode are presented as follows:

$$\varepsilon c2(o/oo) = 2.0 + 0.085(fck - 50)^{0.53} \qquad (20)$$

$$\varepsilon cu2(o/oo) = 2.6 + 35 * \left[\frac{90 - fck}{100}\right]^4 \qquad (21)$$

The strain value calculated from equation (20) can be applied to evaluate the ultimate strain of the concrete with compressive strength above 90MPa. The equation (20) can be used to give both the strain at ultimate strain and the peak strain as given in equation (22):

$$\varepsilon c2(o/oo) = \varepsilon cu2(o/oo) = 2.0 + 0.085(fck - 50)^{0.53} \quad \{for\ fck > 90MPa\} \qquad (22)$$

The coMParison of the experimental values with the values calculated using equation (22) are presented in Figure (7). The Figure suggests that the equation presented in equation (22) agrees well with the experimental value. Although a high coefficient of correlation is not observed (r2=0.35), still the Eurocode based equation is suitable for design as it is safer for most of the experimental samples as well as it is neither too conventional to be uneconomical.

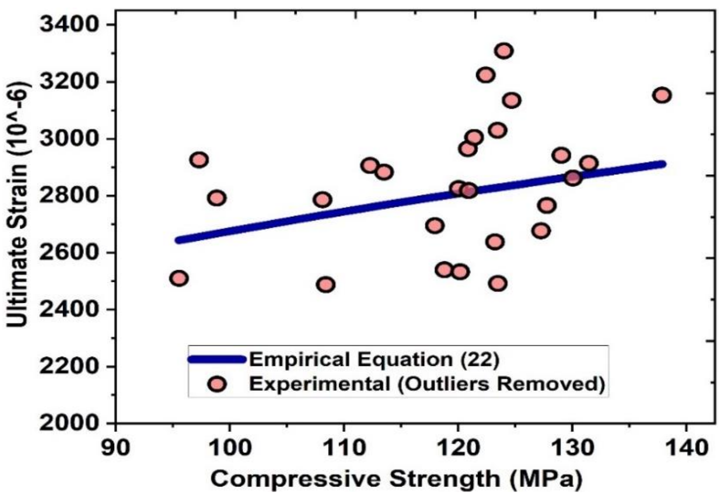


Fig. 7 CoMParison of the strain values obtained from equation (22) with the experimental values (Compressometer)

- Modifications in the equation for calculation of moment of resistance of rectangular section:

Indian standard code IS456 gives the equations for depth of neutral axis and moment of resistance for rectangular section as per equation (23) and (24) as follows:

$$\frac{x_u}{d} = \frac{0.87 * fy * Ast}{0.36 * fck * b * d} \qquad (23)$$

$$Mulim = 0.36 * \frac{xu,max}{d} * \left(1 - 0.42 * \frac{xu,max}{d}\right) * bd^2 * fck \qquad (24)$$

Table 5. Moment calculation based on Modified IS code and Modified Eurocode methods

Cyd str	Calculations for IS Code based stress block Parameters				Calculations for Euro-Code based stress block Parameters			
	K	k_2	$X_u(max)/d$	Moment	K'(EC)	λ/2	$X_u(max)/d$	Moment
95.53	0.26	0.33	0.38	236.90	0.29	0.35	0.32	228.18
97.29	0.26	0.33	0.41	261.08	0.29	0.35	0.34	247.17
98.83	0.26	0.33	0.40	259.06	0.29	0.35	0.33	246.55
105.86	0.26	0.33	0.34	243.25	0.29	0.35	0.30	238.02
107.22	0.26	0.33	0.43	296.11	0.29	0.35	0.35	278.52
108.10	0.26	0.33	0.40	283.05	0.29	0.35	0.33	269.44
108.39	0.26	0.33	0.37	267.52	0.29	0.35	0.32	257.94
109.26	0.26	0.33	0.36	258.68	0.29	0.35	0.30	251.59
111.45	0.26	0.33	0.34	254.61	0.29	0.35	0.30	249.43
112.27	0.26	0.33	0.41	300.26	0.29	0.35	0.34	284.48
112.85	0.26	0.33	0.35	260.19	0.29	0.35	0.30	254.42
113.49	0.26	0.33	0.41	302.32	0.29	0.35	0.34	286.69
117.94	0.26	0.33	0.39	303.61	0.29	0.35	0.33	290.10
118.77	0.26	0.33	0.38	296.40	0.29	0.35	0.32	285.11
120.02	0.26	0.33	0.40	316.48	0.29	0.35	0.34	300.80
120.15	0.26	0.33	0.38	299.40	0.29	0.35	0.32	288.09
120.84	0.26	0.33	0.42	326.40	0.29	0.35	0.34	308.56
120.85	0.26	0.33	0.37	296.00	0.29	0.35	0.31	285.86
120.91	0.26	0.33	0.40	318.43	0.29	0.35	0.34	302.73
121.39	0.26	0.33	0.42	330.04	0.29	0.35	0.35	311.54
122.40	0.26	0.33	0.44	344.16	0.29	0.35	0.36	322.39
123.20	0.26	0.33	0.39	313.65	0.29	0.35	0.33	300.41
123.43	0.26	0.33	0.42	336.94	0.29	0.35	0.35	317.77
123.46	0.26	0.33	0.37	304.98	0.29	0.35	0.32	294.00
123.98	0.26	0.33	0.44	352.84	0.29	0.35	0.36	329.60
124.66	0.26	0.33	0.43	345.91	0.29	0.35	0.35	325.01
127.24	0.26	0.33	0.39	326.42	0.29	0.35	0.33	312.12
127.43	0.26	0.33	0.31	264.37	0.29	0.35	0.27	263.86
127.75	0.26	0.33	0.40	333.28	0.29	0.35	0.33	317.51
129.02	0.26	0.33	0.41	347.16	0.29	0.35	0.34	328.47
130.04	0.26	0.33	0.41	345.15	0.29	0.35	0.34	327.57
131.43	0.26	0.33	0.41	351.98	0.29	0.35	0.34	333.38
137.84	0.26	0.33	0.43	383.53	0.29	0.35	0.35	360.13

For concrete with compressive strength of 90 MPa equation (23) and (24) can be modified based on the obtained stress blocks as given in equation (25) and (26):

$$\frac{x_u}{d} = \frac{0.87 * fy * A_{st}}{0.26 * fck * b * d} \tag{25}$$

$$Mulim = 0.26 * \frac{xu,max}{d} * \left(1 - 0.33 * \frac{xu,max}{d}\right) * bd^2 * fck \tag{26}$$

For Eurocode the equation for the moment can be obtained by merging equations 15 and 19 and putting the values of the stress block parameters. The equation is given as follow in equation (27):

$$Mu = K' * fck * b * x_u * \left(d - \frac{\lambda}{2} * x_u\right) = K' * fck * b * \frac{x_u}{d} * \left(1 - \frac{\lambda}{2} * \frac{x_u}{d}\right) * d^2 = 2.29 * fck * b * \frac{x_u}{d} * \left(1 - 0.35 * \frac{x_u}{d}\right) * d^2 \tag{27}$$

The coMParison of the moments based on the modified IS code procedure and the Modified Eurocode procedure is shown in Figure 8.

As shown in the Figure 8, with few deviations originating from the experimentally obtained strain values, the moment capacity of the beam increases with the increase in the compressive strength. Also, the moments calculated from both the methods differs marginally. The Indian standard code gives a slightly higher value than the corresponding moment calculated from the Eurocode method. The variation arises because the calculations in Eurocode are based on the cylindrical compressive strength whereas Indian standard code is based on the cubical compressive strength. The adopted cube to cylindrical compressive strength in the present study does not coincides with values proposed by Eurocode. However, the variation is not much significant and lies below 5%.

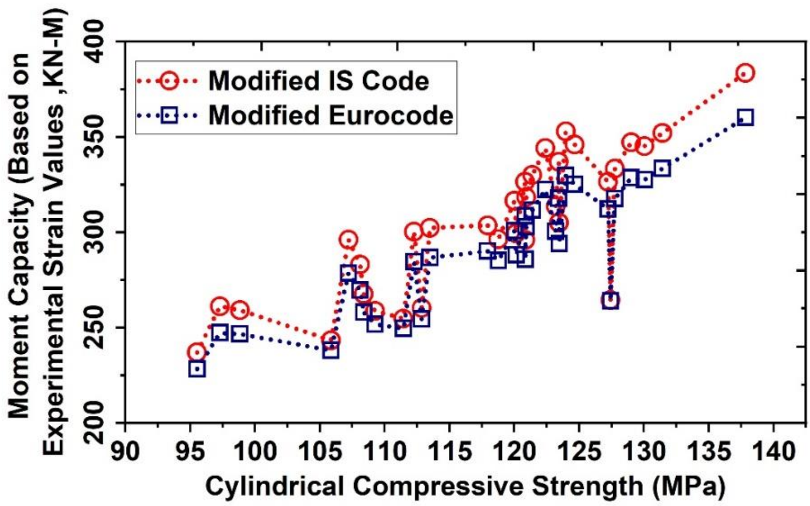


Fig 8. CoMParison of evaluated moments from Modified IS code (equation. 26) and Modified Eurocode (equation 27) methods based on experimental strain values for concrete

7. Conclusions

The stress strain characteristics of concrete changes significantly with increase in concrete compressive strength. Specifically, above 90 MPa the stress strain curves for concrete becomes ideally straight with negligible post peak behaviour. The change in the stress strain characteristics for higher strength concrete makes the existing stress block parameters unsuitable for design of ultra-high strength concrete. The present study attempted to evaluate the stress block parameters for ultra-high strength concrete based on the experimentally determined stress strain characteristics for ultra-high strength concrete. The findings of the study can be concluded as follows:

- The stress strain curves for the concrete above 90MPa compressive strength depicts a straight-line path for the rising limb. Also, the post peak behaviour is negligible leading to equal values for the strain at peak stress and the ultimate strain at failure.
- The stress-strain curves for the LVDT shows a higher strain value as coMPared to the compress meter values. The reason can be attributed to the difference in gauge length ratios adopted for the compress meter and LVDT. Also, the LVDT was attached between the platen and was affected by the strain in greater length of the specimens therefore it gives a higher strain value than the compress meter for similar stress level.
- Based on the observed stress-strain characteristics, the existing stress block with a parabolic and rectangular parts was modified. The modifications proposed includes adoption of a triangular stress block instead of a parabolic stress block. Also, since the strain at peak stress and the ultimate strain coincides, the proposed stress block doesn't have an idealized rectangular upper part.
- Due to the modifications in the shape of the stress block, the stress block parameters also changed. The shape factor k_1 assumes a value of 0.5. The stress block parameter k_2 which gives the location of resulting compressive strength has a value of 0.33 in the modified stress block for compressive strength above 90MPa to 140MPa
- The study indicates that the stress-block parameters which governs the flexural design of RC members needs modifications in existing standards by appropriately taking care of changes in shape factor and stress reduction factor which is depending upon the stress strain characteristics of ultra-high strength concrete wherein strain at peak stress and ultimate strain coincides.

The proposed stress block gives a better representation of the actual stress strain characteristics for the concrete above compressive strength of 90 MPa. The study is supposed to help in updating the existing standards for incorporating the flexural design of ultra-high strength reinforced concrete structures.

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References

[1] Emperger F. Ein graphischer Nachweis der Tragfahigkeit und aller in einem Tragwerke aus Eisenbeton auftretenden Spannungen. Beton und Eisen. 1904; 4:5 306-320.
[2] Whitney CS. Design of reinforced concrete members under flexure or combined flexure and direct compression. ACI Journal Proceedings, ACI 1937.
[3] Hognestad E, Hanson NW, et al. Concrete stress distribution in ultimate strength design. ACI Journal Proceedings, ACI 1955.
[4] Mattock AH, Kriz LB, et al. Rectangular concrete stress distribution in ultimate strength design. ACI Journal Proceedings, ACI 1961.

[5] Oztekin E, Pul S, Husem M. Determination of rectangular stress block parameters for High Performance Concrete. Engineering Structures, 2003; 25: 371-376. https://doi.org/10.1016/S0141-0296(02)00172-4
[6] Attard MM, Stewart MG. Two parameter stress block for High-Strength Concrete. ACI Structural Journal, 1998; 95:3 305- 317. https://doi.org/10.14359/548
[7] Bernardo LFA, Lopes SMR. Neutral axis depth versus flexural ductility in High-Strength Concrete Beams. J. Struct. Eng., 2004; 130:3 452-459. https://doi.org/10.1061/(ASCE)0733-9445(2004)130:3(452)
[8] ACI Committee 318 (2008) "Building Code Requirements for Reinforced Concrete and Commentary ACI 318M-08", Manual of Concrete Practice. American Concrete Institute. Michigan. pp 465. USA.
[9] Standards New Zealand, NZS 3101 (2006), "Concrete Structures Standard, Part 1 - The Design of Concrete Structures", Wellington, New Zealand.
[10] Cetin A, Carrasquillo RL. High- Performance Concrete: Influence of Coarse Aggregates on Mechanical Properties. Journal of ACI Materials, 1998; 95: 252-261. https://doi.org/10.14359/369
[11] Kahn LF, Meyer KF. Rectangular stress block for nonrectangular compression zone. ACI Structural Journal, 1995; 92:3. https://doi.org/10.14359/1131
[12] Mansur MA, Chin MS, Wee TH. Flexural behavior of high-strength concrete beams. ACI Structural Journal, 1997; 94:6 663-673. https://doi.org/10.14359/9726
[13] IS: 456-2000, "Code of Practice for Plain and Reinforced Concrete", Bureau of Indian Standards, New Delhi.
[14] Eurocode 2-2004: Design of concrete structures, European Committee for Standardization.
[15] Ojha, PN, Singh B, Singh P, Singh A, Mandre MK. Study on effect of fly ash and limestone powder on compressive strength of roller coMPacted concrete for dam construction. Journal of Asian Concrete Federation, vol. 8, no. 1, pp. 37-51, Jun.
[16] Ojha PN, Singh B, Prakash S, Singh P, Mandre MK, Kumar S. Effect of high ratio fly ash on roller coMPacted concrete for dam construction. Research on Engineering Structures and Materials, 2022. https://doi.org/10.17515/resm2022.374ma1216
[17] Ojha PN, Singh P, Singh B, Singh A, Mittal P. Fracture behavior of plain and fiber-reinforced high strength concrete containing high strength steel fiber. Research on Engineering Structures and Materials, 2022. https://doi.org/10.17515/resm2022.377ma1228
[18] Ojha PN, Kumar S, Kaura P, Singh B, Singh P. Experimental investigation on effect of corrosion on curvature- ductility relationship of RCC member in flexure. vol. 9, pp. 74-86, May 2022.
[19] IS: 269-2015, 2020, "Ordinary Portland Cement - Specification (Sixth Revision)", Bureau of Indian Standards, New Delhi.
[20] IS: 16714-2018, 2018, "Ground Granulated Blast Furnace Slag for Use in Cement, Mortar & Concrete- Specification", Bureau of Indian Standards, New Delhi.
[21] IS 3812 (2013), "Pulverised Fuel Ash - Specification, Part 1: For use in cement, cement mortar and concrete", Bureau of Indian Standards, New Delhi.
[22] IS 16715-2018, "Ultrafine Ground Granulated Blast Furnace Slag - Specification".
[23] IS 15388 (2003), "Silica Fume - Specification", Bureau of Indian Standards, New Delhi
[24] Hüsken G, Brouwers HJH. A new mix design concept for earth-moist concrete: A theoretical and experimental study. Cement and Concrete Research, 2008; p. 1246 – 1259. https://doi.org/10.1016/j.cemconres.2008.04.002
[25] Yu QL, Spiesz P, Brouwers HJH. Development of cement-based lightweight composites - Part 1: Mix design methodology and hardened properties. Cement and Concrete Composites, 2013; p. 17 – 29. https://doi.org/10.1016/j.cemconcomp.2013.03.030
[26] Ojha PN, Mittal P, Singh A, Singh B, Arora VV. Optimization and evaluation of ultra-high-performance concrete. Journal of Asian Concrete Federation, vol. 6, no. 1. Asian

Concrete Federation, pp. 26-36, Jun. 30, 2020. https://doi.org/10.18702/acf.2020.6.6.1.26

[27] Singh B, Patel V, Ojha PN, Arora VV. Analysis of stress block parameters for high strength concrete. Journal of Asian Concrete Federation, vol. 6, no. 1. Asian Concrete Federation, pp. 1-9, Jun. 30, 2020. https://doi.org/10.18702/acf.2020.6.6.1

[28] Singh B, Arora VV, Patel V. Experimental study on stress strain behaviour of normal and high strength unconfined concrete. Indian Concrete Journal, 2020; 94:4 10-19.

[29] Singh B, Arora VV, Patel V. Study on stress strain characteristics of high strength concrete. Indian Concrete Journal 2018; 92:6 37-43.

[30] Arora VV, Singh B, Durability Studies on Prestressed Concrete made with Portland Pozzolana Cement, Indian Concrete Journal, 2016; 90:8, 41-48.

[31] Ojha PN, Trivedi A, Singh B, S AKN, Patel V, Gupta RK. High performance fiber reinforced concrete - for repair in spillways of concrete dams. Research on Engineering Structures and Materials, 2021. https://doi.org/10.17515/resm2021.252ma0128

[32] Singh B, Ojha PN, Trivedi A, Patel V, Arora VV. Development Of Empirical Equations For Prediction Of Flexural And Split Tensile Strength For Normal And High Strength Concrete With Granite And Calc-Granulite Aggregate, Indian Concrete Journal, November 2021; 95:11 36-46.

[33] Ojha PN, Singh B, Singh A, Patel V, Arora VV. Experimental study on creep and shrinkage behaviour of high strength concrete for application in high rise buildings. Indian Concrete Journal, 2021; 95:2 30-42.

[34] Arora VV, Singh B, Patel V, Daniel Y, Mohapatra BN. Stress-Strain Behaviour and Performance Evaluation of High Strength Steel Fibre Reinforced Concrete. Indian Concrete Journal, 2019; 93:12 54-61.

[35] Arora VV, Singh B, Patel V, Trivedi A. Evaluation of modulus of elasticity for normal and high strength concrete with granite and calc-granulite aggregate," Structural Concrete, vol. 22, no. S1, Jan. 2021 https://doi.org/10.1002/suco.202000023

[36] Ojha PN, Singh B, Kaura P, Singh A. Lightweight geopolymer fly ash sand: an alternative to fine aggregate for concrete production. Research on Engineering Structures and Materials, 2021 https://doi.org/10.17515/resm2021.257ma0205

Supplementary Material

Table 1. Strain at peak stress/ultimate strain for the specimens tested

Individual			Average		
Strength	LVDT	compressometer	Strength	LVDT	compressometer
95.53	3013	2510			
97.29	3509	2926			
98.83	3455	2792			
105.86	3398	2187			
107.22	3368	3104	103.8	3345.4	2637.4
108.1	3553	2786			
108.39	3179	2488			
109.26	3288	2306			
111.45	2936	2165			
112.27	3039	2906			
112.85	2802	2200			
113.49	3240	2883			
117.94	2909	2695			
118.77	2884	2540	117.2	3057.4	2634.8
120.02	3478	2825			
120.15	3152	2533			
120.84	3030	2965			
120.85	3009	2453			
120.91	3152	2818			
121.39	3699	3005			
122.4	3385	3224			
123.2	3225	2638			
123.43	3270	3030			
123.46	3410	2492			
123.98	3450	3309	124.9	3290.5	2823.5
124.66	3064	3135			
127.24	3042	2677			
127.43	3378	1841			
127.75	2853	2766			
129.02	3420	2942			
130.04	3207	2862			
131.43	3416	2914	133.1	3372.0	2976.3
137.84	3493	3153			

Table 2. Stress-block Parameters (IS code)

Cyd str	Cube/ Cyd	Cube Str	Ec	Ecu	r_1	r_2	k_1	S_1	k_3	Ymc	K	k_2
95.53	1.10	105.08	2510	2510	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
97.29	1.10	107.02	2926	2926	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
98.83	1.10	108.71	2792	2792	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
105.86	1.10	116.45	2187	2187	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
107.22	1.10	117.94	3104	3104	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
108.1	1.10	118.91	2786	2786	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
108.39	1.10	119.23	2488	2488	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
109.26	1.10	120.19	2306	2306	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
111.45	1.10	122.60	2165	2165	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
112.27	1.10	123.50	2906	2906	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
112.85	1.10	124.14	2200	2200	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
113.49	1.10	124.84	2883	2883	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
117.94	1.10	129.73	2695	2695	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
118.77	1.10	130.65	2540	2540	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
120.02	1.10	132.02	2825	2825	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
120.15	1.10	132.17	2533	2533	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
120.84	1.10	132.92	2965	2965	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
120.85	1.10	132.94	2453	2453	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
120.91	1.10	133.00	2818	2818	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
121.39	1.10	133.53	3005	3005	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
122.4	1.10	134.64	3224	3224	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
123.2	1.10	135.52	2638	2638	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
123.43	1.10	135.77	3030	3030	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
123.46	1.10	135.81	2492	2492	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
123.98	1.10	136.38	3309	3309	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
124.66	1.10	137.13	3135	3135	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
127.24	1.10	139.96	2677	2677	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
127.43	1.10	140.17	1841	1841	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
127.75	1.10	140.53	2766	2766	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
129.02	1.10	141.92	2942	2942	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
130.04	1.10	143.04	2862	2862	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
131.43	1.10	144.57	2914	2914	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33
137.84	1.10	151.62	3153	3153	1.00	0.00	0.50	0.91	0.77	1.5	0.26	0.33

Table 3. Stress-block Parameters (Eurocode)

Cyd str	Cube/Cyd	Cube Str	Ec	Ecu	λ	η	αcc	S1	Ycc	K'(EC)	k2
95.53	1.10	105.08	2510	2510	0.70	0.80	0.85	0.91	1.5	0.29	0.35
97.29	1.10	107.02	2926	2926	0.70	0.80	0.85	0.91	1.5	0.29	0.35
98.83	1.10	108.71	2792	2792	0.70	0.80	0.85	0.91	1.5	0.29	0.35
105.86	1.10	116.45	2187	2187	0.70	0.80	0.85	0.91	1.5	0.29	0.35
107.22	1.10	117.94	3104	3104	0.70	0.80	0.85	0.91	1.5	0.29	0.35
108.1	1.10	118.91	2786	2786	0.70	0.80	0.85	0.91	1.5	0.29	0.35
108.39	1.10	119.23	2488	2488	0.70	0.80	0.85	0.91	1.5	0.29	0.35
109.26	1.10	120.19	2306	2306	0.70	0.80	0.85	0.91	1.5	0.29	0.35
111.45	1.10	122.60	2165	2165	0.70	0.80	0.85	0.91	1.5	0.29	0.35
112.27	1.10	123.50	2906	2906	0.70	0.80	0.85	0.91	1.5	0.29	0.35
112.85	1.10	124.14	2200	2200	0.70	0.80	0.85	0.91	1.5	0.29	0.35
113.49	1.10	124.84	2883	2883	0.70	0.80	0.85	0.91	1.5	0.29	0.35
117.94	1.10	129.73	2695	2695	0.70	0.80	0.85	0.91	1.5	0.29	0.35
118.77	1.10	130.65	2540	2540	0.70	0.80	0.85	0.91	1.5	0.29	0.35
120.02	1.10	132.02	2825	2825	0.70	0.80	0.85	0.91	1.5	0.29	0.35
120.15	1.10	132.17	2533	2533	0.70	0.80	0.85	0.91	1.5	0.29	0.35
120.84	1.10	132.92	2965	2965	0.70	0.80	0.85	0.91	1.5	0.29	0.35
120.85	1.10	132.94	2453	2453	0.70	0.80	0.85	0.91	1.5	0.29	0.35
120.91	1.10	133.00	2818	2818	0.70	0.80	0.85	0.91	1.5	0.29	0.35
121.39	1.10	133.53	3005	3005	0.70	0.80	0.85	0.91	1.5	0.29	0.35
122.4	1.10	134.64	3224	3224	0.70	0.80	0.85	0.91	1.5	0.29	0.35
123.2	1.10	135.52	2638	2638	0.70	0.80	0.85	0.91	1.5	0.29	0.35
123.43	1.10	135.77	3030	3030	0.70	0.80	0.85	0.91	1.5	0.29	0.35
123.46	1.10	135.81	2492	2492	0.70	0.80	0.85	0.91	1.5	0.29	0.35
123.98	1.10	136.38	3309	3309	0.70	0.80	0.85	0.91	1.5	0.29	0.35
124.66	1.10	137.13	3135	3135	0.70	0.80	0.85	0.91	1.5	0.29	0.35
127.24	1.10	139.96	2677	2677	0.70	0.80	0.85	0.91	1.5	0.29	0.35
127.43	1.10	140.17	1841	1841	0.70	0.80	0.85	0.91	1.5	0.29	0.35
127.75	1.10	140.53	2766	2766	0.70	0.80	0.85	0.91	1.5	0.29	0.35
129.02	1.10	141.92	2942	2942	0.70	0.80	0.85	0.91	1.5	0.29	0.35
130.04	1.10	143.04	2862	2862	0.70	0.80	0.85	0.91	1.5	0.29	0.35
131.43	1.10	144.57	2914	2914	0.70	0.80	0.85	0.91	1.5	0.29	0.35
137.84	1.10	151.62	3153	3153	0.70	0.80	0.85	0.91	1.5	0.29	0.35

Table 4. Moment Capacity (IS code)

Cyd str	Cube/ Cyd	Cube Str	Ec	Ecu	Esu	K	k_2	Xu(max)/d	Moment
95.53	1.10	105.08	2510.00	2510.00	4175.00	0.26	0.33	0.38	236.90
97.29	1.10	107.02	2926.00	2926.00	4175.00	0.26	0.33	0.41	261.08
98.83	1.10	108.71	2792.00	2792.00	4175.00	0.26	0.33	0.40	259.06
105.86	1.10	116.45	2187.00	2187.00	4175.00	0.26	0.33	0.34	243.25
107.22	1.10	117.94	3104.00	3104.00	4175.00	0.26	0.33	0.43	296.11
108.10	1.10	118.91	2786.00	2786.00	4175.00	0.26	0.33	0.40	283.05
108.39	1.10	119.23	2488.00	2488.00	4175.00	0.26	0.33	0.37	267.52
109.26	1.10	120.19	2306.00	2306.00	4175.00	0.26	0.33	0.36	258.68
111.45	1.10	122.60	2165.00	2165.00	4175.00	0.26	0.33	0.34	254.61
112.27	1.10	123.50	2906.00	2906.00	4175.00	0.26	0.33	0.41	300.26
112.85	1.10	124.14	2200.00	2200.00	4175.00	0.26	0.33	0.35	260.19
113.49	1.10	124.84	2883.00	2883.00	4175.00	0.26	0.33	0.41	302.32
117.94	1.10	129.73	2695.00	2695.00	4175.00	0.26	0.33	0.39	303.61
118.77	1.10	130.65	2540.00	2540.00	4175.00	0.26	0.33	0.38	296.40
120.02	1.10	132.02	2825.00	2825.00	4175.00	0.26	0.33	0.40	316.48
120.15	1.10	132.17	2533.00	2533.00	4175.00	0.26	0.33	0.38	299.40
120.84	1.10	132.92	2965.00	2965.00	4175.00	0.26	0.33	0.42	326.40
120.85	1.10	132.94	2453.00	2453.00	4175.00	0.26	0.33	0.37	296.00
120.91	1.10	133.00	2818.00	2818.00	4175.00	0.26	0.33	0.40	318.43
121.39	1.10	133.53	3005.00	3005.00	4175.00	0.26	0.33	0.42	330.04
122.40	1.10	134.64	3224.00	3224.00	4175.00	0.26	0.33	0.44	344.16
123.20	1.10	135.52	2638.00	2638.00	4175.00	0.26	0.33	0.39	313.65
123.43	1.10	135.77	3030.00	3030.00	4175.00	0.26	0.33	0.42	336.94
123.46	1.10	135.81	2492.00	2492.00	4175.00	0.26	0.33	0.37	304.98
123.98	1.10	136.38	3309.00	3309.00	4175.00	0.26	0.33	0.44	352.84
124.66	1.10	137.13	3135.00	3135.00	4175.00	0.26	0.33	0.43	345.91
127.24	1.10	139.96	2677.00	2677.00	4175.00	0.26	0.33	0.39	326.42
127.43	1.10	140.17	1841.00	1841.00	4175.00	0.26	0.33	0.31	264.37
127.75	1.10	140.53	2766.00	2766.00	4175.00	0.26	0.33	0.40	333.28
129.02	1.10	141.92	2942.00	2942.00	4175.00	0.26	0.33	0.41	347.16
130.04	1.10	143.04	2862.00	2862.00	4175.00	0.26	0.33	0.41	345.15
131.43	1.10	144.57	2914.00	2914.00	4175.00	0.26	0.33	0.41	351.98
137.84	1.10	151.62	3153.00	3153.00	4175.00	0.26	0.33	0.43	383.53

Table 5. Moment Capacity (Eurocode)

Cyd str	Cube/Cyd	Cube Str	Ec	Ecu	k_4	K'(EC)	λ/2	Xu(max)/d	Moment
95.53	1.10	105.08	2510.00	2510.00	1.45	0.29	0.35	0.32	228.18
97.29	1.10	107.02	2926.00	2926.00	1.35	0.29	0.35	0.34	247.17
98.83	1.10	108.71	2792.00	2792.00	1.38	0.29	0.35	0.33	246.55
105.86	1.10	116.45	2187.00	2187.00	1.55	0.29	0.35	0.30	238.02
107.22	1.10	117.94	3104.00	3104.00	1.31	0.29	0.35	0.35	278.52
108.10	1.10	118.91	2786.00	2786.00	1.38	0.29	0.35	0.33	269.44
108.39	1.10	119.23	2488.00	2488.00	1.45	0.29	0.35	0.32	257.94
109.26	1.10	120.19	2306.00	2306.00	1.51	0.29	0.35	0.30	251.59
111.45	1.10	122.60	2165.00	2165.00	1.56	0.29	0.35	0.30	249.43
112.27	1.10	123.50	2906.00	2906.00	1.35	0.29	0.35	0.34	284.48
112.85	1.10	124.14	2200.00	2200.00	1.55	0.29	0.35	0.30	254.42
113.49	1.10	124.84	2883.00	2883.00	1.36	0.29	0.35	0.34	286.69
117.94	1.10	129.73	2695.00	2695.00	1.40	0.29	0.35	0.33	290.10
118.77	1.10	130.65	2540.00	2540.00	1.44	0.29	0.35	0.32	285.11
120.02	1.10	132.02	2825.00	2825.00	1.37	0.29	0.35	0.34	300.80
120.15	1.10	132.17	2533.00	2533.00	1.44	0.29	0.35	0.32	288.09
120.84	1.10	132.92	2965.00	2965.00	1.34	0.29	0.35	0.34	308.56
120.85	1.10	132.94	2453.00	2453.00	1.46	0.29	0.35	0.31	285.86
120.91	1.10	133.00	2818.00	2818.00	1.37	0.29	0.35	0.34	302.73
121.39	1.10	133.53	3005.00	3005.00	1.33	0.29	0.35	0.35	311.54
122.40	1.10	134.64	3224.00	3224.00	1.29	0.29	0.35	0.36	322.39
123.20	1.10	135.52	2638.00	2638.00	1.41	0.29	0.35	0.33	300.41
123.43	1.10	135.77	3030.00	3030.00	1.33	0.29	0.35	0.35	317.77
123.46	1.10	135.81	2492.00	2492.00	1.45	0.29	0.35	0.32	294.00
123.98	1.10	136.38	3309.00	3309.00	1.28	0.29	0.35	0.36	329.60
124.66	1.10	137.13	3135.00	3135.00	1.31	0.29	0.35	0.35	325.01
127.24	1.10	139.96	2677.00	2677.00	1.40	0.29	0.35	0.33	312.12
127.43	1.10	140.17	1841.00	1841.00	1.70	0.29	0.35	0.27	263.86
127.75	1.10	140.53	2766.00	2766.00	1.38	0.29	0.35	0.33	317.51
129.02	1.10	141.92	2942.00	2942.00	1.34	0.29	0.35	0.34	328.47
130.04	1.10	143.04	2862.00	2862.00	1.36	0.29	0.35	0.34	327.57
131.43	1.10	144.57	2914.00	2914.00	1.35	0.29	0.35	0.34	333.38
137.84	1.10	151.62	3153.00	3153.00	1.31	0.29	0.35	0.35	360.13