Nonlinear analysis of hybrid reinforced concrete beams under flexural load

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Abstract. In recent years, concrete having a compressive strength of 60 MPa and more is being used for high-rise buildings and long span bridges, but high strength concrete is more expensive than normal strength concrete and became commercially used in engineering construction. This material has to be placed where it should be in order to get an economical consideration.

This study introduces analyses of a new two layers reinforced concrete beam where high strength concrete in the compression zone and normal strength concrete in the tension zone are assumed based on experiences of previous laboratory.

The beam specimens were solved numerically using nonlinear finite element program provided by ABAQUS 6.12 software for static load to verify the same using experiment. An agreement between analysis and experimental results was obtained, and less than 11.4% has been put as acceptable limit.

Keywords
Abaqus 6.12-2008, FEM, High strength concrete beam, Compressive strength, HSC, NSC, flexural

1. Introduction
Concrete a compound consisting of aggregates surrounded in a matrix of cement paste containing possible pozzolans, has two key parts – cement paste and aggregates. The strength of concrete relies upon the strength of those parts, their deformation properties, and also the adhesion between the paste and aggregates [1]. It is potential to create concrete up to 120 MPa compressive strength by enhancing the strength of the cement paste, which may be controlled thru the selection of water-cement ratio, kind and quantity of admixtures [2]. Concrete is a comparatively brittle material whose tensile strength is low in comparison with its compressive strength; this prevents its economical use in structural members, which are subjected to tension either completely or partly as flexural members, like beams.

Now-a-days, steel and concrete can be produced with relatively higher strength than ordinary, because of development in material science knowledge and therefore, availability of various types of mineral and chemical admixtures and very powerful first-rate plasticizers, concrete with a compressive strength up to 120 MPa may be prepared compressive strength is at least 41 MPa in America or 60 MPa in Europe. [3,4]

In the design of flexural members, the decision to use either high or low strength concrete or steel depends on economies, the importance of special requirements, member size and the concerning mechanical behavior as deflection, ductility and crack width [5]. The nature of composite construction is layered parts that combination different kinds of concrete together with standard reinforcement, fiber reinforcement or with layers of fiber-reinforced polymer composite [6,7,8,9]. Such constructions are frequently referred to as hybrid constructions, and also the key challenge with this kind of
construction is the interface and bond between the materials [10,11,12]. Beams of more than one homogeneous material are commonly used. Wooden beams are the original founder of hybrid beam is John Hillman in 1994, but the development of design limit stress, fabrication process and structural validation started in 1999 when the Transportation Research Board (TRB), United States of America, gave a variety of Innovations Deserving Exploratory Analysis (IDEA). In the present study a finite element method by using software ABAQUS 6.12-2008 is used to analyze a nine experimental hybrid beams failed in flexure [16]. A good agreement analysis results were found compared with experimental works.

2. Material Modeling and Failure Criterion

The uniaxial stress-strain relationship for the concrete in compression assuming the yield criterion is the basis for an elastic - perfectly plastic model for normal concrete as shown in figure (1) [13]. The model response is elastic until the effective stress reaches the value of \( f' c \). For normal and high-strength concrete the multilinear model are adopted to idealize the stress-strain behavior as shown in figure (2). It can be defined by the following equations (1,2,3)

![Figure 1. Representation of the concrete constitutive model [13].](image1)

![Figure 2. Uniaxial stress-strain curve for normal strength concrete [14].](image2)

![Figure 3. Hognestad compressive stress-strain curve for concrete.](image3)

Hognestad model is one of the earliest, widely used mathematical models for uniaxial stress-strain curve, which is proposed by Hognestad [15].

The ascending part of the curve is a parabola given by the equation,
\[
\sigma = f'_c \left( \frac{e}{e_0} \right) \left( 2 - \frac{e}{e_c} \right) \quad \text{......... (1)}
\]

where \( e_c = 2 \frac{f'_c}{E_i} \quad \text{......... (2)} \)

Beyond the maximum compressive stress, the model is represented by a straight line,

\[
\sigma = \left[ 1 - 0.15 \left( \frac{e}{e_{cu}} \right) \right] \cdot f'_c \quad \text{......... (3)}
\]

* In above equations, instead of \( f'_c \) used \( 0.3 \ f'_c \) in NSC & \( 0.6 \ f'_c \) in HSC [16] for straight part, before cracking with ultimate strain, \( e_{cu} \), equal to 0.0035 after which crushing of the concrete is assumed to occur.

3. Hybrid Reinforced Concrete Beams by (alshididi) [16]

Simply supported hybrid reinforced concrete beams tested by Al-Shadidi [16] are analyzed in the present investigation. Two mixes were designed to obtain concrete of 25 and 70 MPa nominal compressive strengths. These beams were subjected to loads equal to two third points. The dimensions of each beam are (2000x240x160 mm).

The geometry and details of beams are shown in figures (4 and 5) and table (1) shows the specifications of the beams used in the present study.

![Figure 4](image-url)

**Figure 4.** Longitudinal section in the beam (all dimensions in mm). [16]
Figure 5. Beams Cross-sections details [16].

From figure (5) the difference in simulation to every group is in type strength of concrete (NSC1, NSC2, NSC3) all section are normal strength concrete; (HSC1, HSC2, HSC3) high strength concrete and (HYSC1, HYSC2, HYSC3) hybrid concrete with thickness (40,50,75) mm, respectively.

| Notation | (HSC) layer | Main Rein. | fy (Mpa) | fc (Mpa) | Ec (Gpa) | Stirrups | spacing mm | Pu (kN) |
|----------|-------------|------------|----------|----------|----------|----------|------------|---------|
| NSC1     | 0           | 2φ10       | 520      | 25.1     | 26.7     | φ6       | 100        | 73.5    |
| HSC1     | 240         | 2φ10       | 520      | 72       | 37       | φ6       | 100        | 84      |
| HYSC1    | 40          | 2φ10       | 520      | 25.72    | 25.1,37.5| φ6       | 100        | 82      |
| NSC2     | 0           | 2φ12       | 560      | 24.1     | 23.6     | φ6       | 100        | 92      |
| HSC2     | 240         | 2φ12       | 560      | 69.5     | 36.7     | φ6       | 100        | 90      |
| HYSC2    | 50          | 2φ12       | 560      | 26.70    | 24.5,39  | φ6       | 100        | 94      |
| NSC3     | 0           | 4φ16       | 596      | 26.5     | 27.2     | φ10      | 100        | 192     |
| HSC3     | 240         | 4φ16       | 596      | 69       | 35.4     | φ10      | 100        | 256     |
| HYSC3    | 75          | 4φ16       | 596      | 25.5,73  | 24.7,38  | φ10      | 100        | 284     |

*Note: Assumed constant parameters are used in Table (2)

Table 2. constant parameters

|  \( v \) | Poisson’s ratio for NSC | 0.17 |
|  \( v \) | Poisson’s ratio for HSC | 0.2  |
|  \( v \) | Poisson’s ratio for steel | 0.3  |
|  \( E_s \) | Young’s modulus for steel (Gpa) | 200 |

4. Simulation In Finite Element

4.1 Modeling of Concrete Beams

The ABAQUS finite component software was once employed in this study to simulate the behavior of the experimental beams [16]. ABAQUS/Standard used to be chosen simulation, Reinforcement in an exceedingly concrete beam used to be created as 3D beam typical with cross section definite in ABAQUS/CAE.
4.2 Properties of Materials

ABAQUS has options set to substantial reference library within the engineering information sections. Moreover, it is able to choose a material from the reference library or it may be automatically coming into the material properties of ABAQUS/CAE. The material typical in Abaqus/CAE needs completely different coefficients. The yield surface consists of 4 parameters. The Poisson's ratio(\(\nu\)) controls the quantity modifications of concrete for stresses below vital worth that is the beginning of inelastic behavior. Once the critical stress rate is got concrete exhibits a rise in plastic capacity stressed [17]. This behavior is taken under consideration by an important parameter in table (3)[18]

| Table 3, constant parameter of concrete damage plasticity (C.D.P) |
|---------------------------------------------------------------|
| the angle of dilation(\(\psi\)) | (15-36) ° |
| Eccentricity (\(e\)) | 0.1 |
| (\(fb0/fc0\)) | 1.16 |
| \(Kc\) | 2/3 |

4.3 Meshing

Meshing plays a significant part within the FEA since the properties and main connections area unit assumed over the discretized parts and expressed mathematically on the desired known as nodules. Those increasing the numeral of parts during finite element typical can increase accurately however, at a similar purpose it'll takings longer to resolution the equations. Element kind used is C3D8 element nature provided additional stable results.

4.4 Loads and Boundary Conditions

The reinforced concrete beams were made of specified concrete to be tested simply supported under two equal third point loads external through the nodes of two adjacent rows of elements bound the actual load line at the top surface of the beam.
5. Result and discussion Load-Deflection Behavior
In figures (9) to (17) curves show that beams fail by yielding of tension reinforcement and exhibit three different stages starting from pre-cracking linear stage where both concrete and steel are still in their elastic response portions due to small strains. The range of this portion, on the curve, depends on the the behavior of concrete in tension ($\sigma$) and stress value before that failure, what is known as Modulus of Rupture or Flexural Strength or Bend Strength "$f_r$" of concrete in the tension zone then the curve moves to the second stage of the elastic-plastic in which the cracks begin in the lowest layer of the tensile zone, with the loading increase; the number of cracks and expand, linkage and then bridge with each other's, then reach the final stage of the plastic phase the failure phase. By comparing the results between experimental work and numerical by finite element, it is noted that the convergence of the results range (0.39%-6.2%) in finite which than exp. [16]

Maximum deflection of HSC beams was more than that of NSC beams for HSC beams sustained higher ultimate load and this allows them to withstand higher deflections (higher energy absorption).

When HSC Layer Thickness increases; increase loading is observed to resist the stresses and sustained higher ultimate load.

However, it is generally shown that increasing HSC layer thickness has a positive effect on general load-deflection behavior of the beams, leading to significantly smaller deflections.

| Table 4. Experimental and finite element results of ultimate loads |
|-----------------------------------------------|
| beams          | $P_{U_{Exp}}$ [16] | $P_{U_{Num.}}$ | $P_{U_{Num.}}/P_{U_{Exp.}}$ |
| NSC1           | 73.5              | 70             | 0.952                      |
| HSC1           | 84                | 85             | 1.011                      |
| HYSC1          | 82                | 81.6           | 0.995                      |
| NSC2           | 92                | 84.8           | 0.921                      |
| HSC2           | 90                | 87.3           | 0.97                       |
| HYSC2          | 94                | 83.3           | 0.886                      |
| NSC3           | 192               | 181.5          | 0.945                      |
| HSC3           | 256               | 250            | 0.976                      |
| HYSC3          | 284               | 270.6          | 0.952                      |
| Mean $\mu$ (%) |                  |                | 0.936                      |
| Coefficient of Variation (%) |                |                | 4.3877                     |

Table (4) shows that the mean value of finite element ultimate load to the experimental ultimate load of (0.936) and coefficient of variation of 4.3877%. This ratio was once higher than 1.0 for most of
the analyzed beams indicating the slightly, “stronger” reaction of the finite element models than the experimental beams. Crack patterns of failure load of beam HSC3 for both experimental and numerical specimens are shown in figures (19) and (20), respectively.

**Figure 12.** Load-Deflection at mid span for Homogeneous 25MPA Concrete Beam (NSC.2)

**Figure 13.** Load-Deflection at mid span for Homogeneous 70MPA Concrete Beam (HSC.2)

**Figure 14.** Load-Deflection at mid span for Hybrid Concrete Beam (HYSC.2) thickness HSC=(50mm)

**Figure 9.** Load-Deflection at mid span for Homogeneous 25MPA Concrete Beam (NSC.1)

**Figure 10.** Load-Deflection at mid span for Homogeneous 70MPA Concrete Beam (HSC.1)

**Figure 11.** Load-Deflection at mid span for Hybrid Concrete Beam (HYSC.1) thickness HSC=(40mm)
Figure 17. Load-Deflection at mid span for Hybrid Concrete Beam (HYSC.3) thickness HSC=(75mm)

Figure 15. Load-Deflection at mid span for Homogeneous 25MPA Concrete Beam (NSC.3)

Figure 16. Load-Deflection at mid span for Homogeneous 70MPA Concrete Beam (HSC.3)

Figure 18. Load-Deflection at mid span for Hybrid Concrete Beams in finite element

Figure 19. Crack patterns of the analyses HSC3 beam

Figure 20. Crack patterns of the tested HSC3 beam alshadidi [16]
6. Conclusions

1) The failure Pattern of HSC Beam acceptable exploration ABAQUS and also the failure load that which measurement from ABAQUS is very near to the failure load expected by experimental works.
2) As compared to numerical Analysis, the experimental work of the deflection is adequate and within the allowable limits.
3) The accuracy of the computational model adopted to predict the behavior of beams at different stages of loading up to failure.
4) The deviation between numerical results increases with increasing the depth of the high strength concrete zone layers. This may be due to high stresses induced on the elements representing the accurate results.
5) The ratio between numerical and experimental results was less than 11.4% which is acceptable results.

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