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Finite Element Modelling of Laboratory Tests on Reinforced Concrete Beams Containing Recycled Aggregate Concrete

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ABSTRACT

The predictive accuracy of the finite element (FE) based packages are broadly based on the compatibility of adopted non-linear numerical procedures and incorporated material models. However, the routine way to define concrete material is not applicable to the concretes containing substitute materials in place of conventional concrete ingredients. Therefore, in this work, appropriate definition of materials in terms of stress-strain relations have been utilized to simulate the experimental work of RC beams containing coarser fractions of recycled concrete aggregates (RCA). The entire work has been carried out into two phases; an experimental work and the simulation of experimental work using FEA package, ABAQUS. In the experimental part, three number of full-scaled beam specimens were tested to failure through four-point monotonous loading. The replacement level of natural coarse aggregates was taken as 0.0, 50 and 100% by direct substitution. In the simulation phase, in addition to laboratory evaluated properties like compressive stress, tensile stress and elastic modulus, the measured stress-strain relationship for reinforcing steel and constitutive relationship for recycled aggregate concrete (RAC) reported in the literature have been considered as an input. The stress-strain relationships of RAC selected from the literature has been treated as user defined model. Besides the strength, serviceability in terms of deflections, crack patterns and load deformation characteristics of simulated beams have been investigated and compared with those of laboratory tested beam specimens.

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NOMENCLATURE

FEA	Finite element analysis	NA	Natural aggregate
RC	Reinforced concrete	NAC	Natural aggregate concrete
RCC	Reinforced cement concrete	LVDT	Linear variable differential transformer

1. INTRODUCTION

A good number of FEA packages have been developed to evaluate the response of RCC structural forms during last few decades. The performance in terms of accuracy of these packages are broadly based on the adopted non-linear numerical procedures and incorporated material models [1]. These models mainly categorised into two classes such as empirical models and continuum mechanics-based models [2]. Initially continuum mechanics-based models were confined to isotropic and homogeneous materials. However, with an advancement in technology and broadened requirement, these theories have been extended to heterogeneous materials like concrete [3]. On the other hand, in the construction industry, sustainability become an urgent necessity of an hour, and to that end, utilization of waste products as a substitute material for concrete ingredients become evident [4]. Eventually, the use of recycled aggregates in concrete making and structural applications of such concrete is started gaining momentum [5, 6]. However, the analysis of such structural elements containing RAC requires special attention as the concrete models available in these softwares are not compatible with the modified properties and stress-strain relationships of RAC. Because RAC beams exhibit higher strains and deflection and lower or similar cracking moments than

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conventional ones [7, 8]. Nevertheless, some packages offer freedom to the users to use laboratory evaluated index properties and measured stress-strain relationships. ABAQUS is one of such softwares which offers freedom to users to use user-defined material-models with ease.

As discussed in the preceding paragraph, the use of FEA packages has become the essential component of the modern analysis and design procedures pertaining to civil engineering structures [9]. With the rapid growth of FE techniques and material constitutive models in the last decade, the numerical methods have become more significant, since they can successfully simulate difficult or even complicated cases [10]. An important part of numerical analysis has been the development of a numerical method that works well with measured uniaxial stress-strain relationships [11]. Computer programs like LS-Dyna, ABAQUS and ANSYS are being extensively used [12]. On the contrary, some analysis software's have the limitations regarding the simulation of appropriate support conditions. For instance, to establish the line contact in order to simulate the steel rollers as point loads and supports to carry out the analysis of four-point bending test of RCC beam specimens. The software is programmed in such a way that only finite dimensions can create the support and load contacts. Therefore, in some studies [13, 14] steel plates (finite dimensions) in place of steel rollers were considered to define and simulate the support condition (as no alternative left to simulate rollers) even though the companion laboratory tests on RCC beams consist of steel rollers. Besides this, the input parameters assigned prior to simulation of structural components or structure as a whole plays very crucial role especially when alternate materials for concrete ingredients are to be used aiming sustainable development [15, 16]. It should be noted that the routine way to define concrete material is not applicable to the concretes containing substitute materials in place of conventional ingredients. In such a scenario, it becomes inevitable to carry out the simulation in the way the user manual administers. Few software offer liberty to the users to describe material behaviours employing measured stress-strain relationships as an input.

Typically, a FEA package is deemed to be competent in producing reasonable predictions when the variation between the anticipated and the experimentally measured values of certain structural attributes is less than 20% of the measured values, such structural characteristics typically include the load vs. displacement profiles, the load-carrying capacity, etc. and the qualitative behaviour pattern matches, such as the crack patterns at various load stages are also considered. Furthermore, FEA software is called objective and generic when it can accurately estimate structural behaviour for any structural concrete setup without recalibrating the constitutive model or parameters [3].

In this work, ABAQUS was employed to simulate numerically the experimental work of RC beams of concrete containing coarse RCA, subjected to pure flexure failure. To ascertain the efficacy of the FE model, the typical constitutive model for RCA-concrete available in literature was examined with the corresponding experimental results of the beam specimens. Moreover, the flexural behaviour of beams obtained from the numerical-analysis was compared with the measured results in terms of the flexure strength, load deflection behaviour and crack patterns.

2. EXPERIMENTAL INVESTIGATION

In this experimental investigation, total three number of beam specimens were cast and tested to the failure in order to assess the structural behaviour of RCA-concrete beams. All the beam specimens were 2100 mm long and designed for a cross-section of 125 mm width and 250 mm depth according to Indian Standards IS 456 [17], and were tested over 1800 mm simply supported span with 150 mm overhangs on each side. For all the beams, the shear-span of 600 mm was considered. The four-point loading was applied to the beam specimens in order to get no shear force in the region of constant moment. The region of constant moment was defined 600 mm, which was equal to the one-third of effective span. The nominal top reinforcement was curtailed in the region of constant moment to eliminate the effect of it on pure flexure failure, as the beam section was desired to be singly reinforced. Thermo-Mechanically Treated (TMT) steel rebars conforming to IS 1786 [18] were used to form cages. The measured yield strength of Fe500 grade rebar was 500 MPa. The reinforcement details of the beam specimens are depicted in Figure 1.

The concrete containing RCA extracted from the debris of demolished RCC structures was used to cast test specimens. The control concrete mixture containing natural coarse aggregates was designed by absolute volume method, conforming IS 10262 [19] whereas the mix for RAC was designed by the direct weight replacement method (DWRM). In the DWRM, the natural coarse aggregates were replaced with an equivalent weight of recycled coarse aggregate particles. The weight proportion of recycled coarse aggregates in

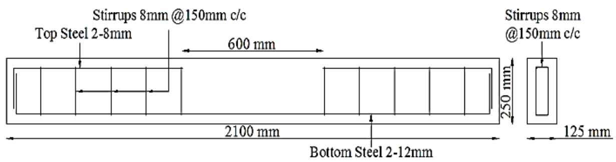


Figure 1. Typical reinforcement detail

TABLE 1. Mixture composition (in terms of ratios by weight) and measured properties of the NAC and the RCA-concretes

Mix Id	RCA replacement level	Cement	Mixing Water	Fine aggregates	Coarse NA (4.75-20 mm)	Coarse RCA (4.75-20 mm)	HRWRA (% by weight of cement)	Compressive strength (MPa)
R0	0	1.0	0.45	1.92	2.82	0.00	1.0	30.00
R50	50	1.0	0.45	1.92	1.41	1.41	1.0	28.50
R100	100	1.0	0.45	1.92	0.00	2.82	1.0	26.50

TABLE 2. Simmary of test and simulation results

Beam Id	Replacement ratio (%)	Measured ultimate load (kN)	Ultimate load predicted by ABAQUS (kN)	Measured displacement at ultimate load (mm)	Displacement at ultimate load predicted by ABAQUS (mm)
R0	0	84.00	87.72	14.10	14.41
R50	50	80.50	84.37	12.96	13.70
R100	100	78.00	81.65	12.01	12.40

the total coarse aggregates of the concrete mix is specified as the recycled coarse aggregate replacement percentage. The replacement level of natural coarse aggregates with RCA in percentage was as follows: 0.0, 50 and 100%. Control concretes are identified in this investigation by the generic name of NAC whereas the concretes containing full fractions of the recycled coarse aggregates are identified by the generic name of RCA-concrete. Except for substitution of the natural coarse aggregate particles with the recycled coarse aggregate, the other constituents in these two concrete types were nominally the same. The mixture composition and concrete compressive strength using 150 x 300 mm cylindrical specimens of the NAC and the RCA-concrete used in the experimental programme are given in Table 1.

The first placeholder in the nomenclature of the beam represents replacement of natural coarse aggregate in concrete. The second placeholder (digits) indicates the level of replacement in percentage. For example, in the beam specimen R100 indicate 100% replacement of natural coarse aggregate.

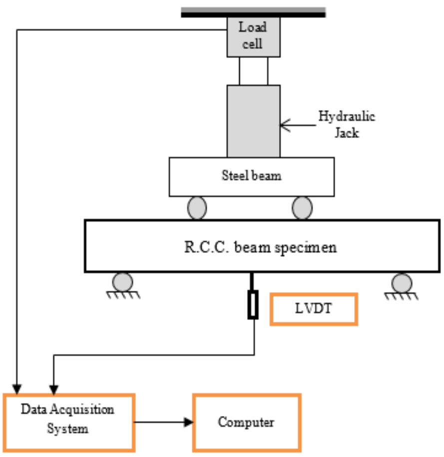


Figure 2. Schematic test set-up for beam tests

After 24 hours of casting, the formwork was removed, and all the beam specimens were kept in a normal environment condition, enclosed with wet jute gunny bags until they were tested at 28 days of age. The beam specimens were surface dried after 28 days of curing, followed by application of a single layer of white wash to facilitate detection of crack formation and growth. The test setup for a typical beam in four-point loading across a simply supported span of 1800 mm is illustrated in Figure 2. On the side faces of the beams, an orthogonal grid of lines spaced 50 mm vertically and 100 mm horizontally was marked to aid with crack tracing. Each specimen was tested in a load frame of capacity 2000 kN in order to evaluate load carrying capacity of the beam specimens. The monotonically increased load was applied on the top face of the beams with the help of a 1000 kN capacity hydraulic jack until the beam failed. Before the actual loading, preloading was performed to ensure that the load cell and LVDT sensor function normally. The applied load was measured with the load cell. At the load point, two rollers were used to transfer equal applied load to each support through the steel beam arrangement as seen in Figure 2. Hinge and roller supports are illustrated in Figure 2 and the deflections at the load-point were measured using LVDT.

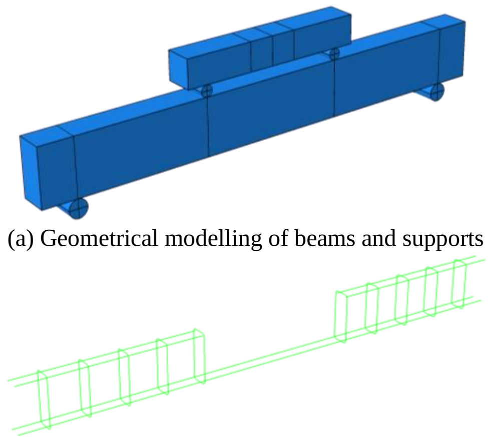
3. THE FINITE ELEMENT MODELLING

A FEA package is known for realistic predictions of the behaviour of structural forms in terms of structural characteristics. Load carrying capacity, load-deformation, moment-curvature relations and pattern matches like the crack patterns corresponding to different load stages and failure modes are some of them. Moreover, it should be capable of predicting the realistic behaviour of any structural form without recalibration. The main requirements of FEA modelling are as follows: 1) to adopt a constitutive relationship to describe the material nonlinearity of concrete, steel rebars and their mutual interactions; 2) to incorporate a nonlinear numerical procedure that is effectively capable of implementing internal stresses redistribution forced by material nonlinearity against imposed external loadings plus a numerical description on cracking process.

Though the peak stress value is assumed to be implicit due to the gradual degradation of the stiffness related to residual material strength after a peak stress yet the numerical procedural scheme adopted by most of the softwares were developed independent of material models. The majority of FEA packages employed an iterative procedures based on numerical techniques like Newton-Raphson method. The iterative procedure is to account for the checks for redistribution of stresses during crack openings and crack closure, besides the simultaneous checks on convergence in each iteration. The iterations are repeated till the convergence criterion met resulting into attainment of predefined minimum value of residual forces estimated from the use of equilibrium equations.

3. 1. Geometry Definition There are several approaches available to create geometry of an element in ABAQUS out of which the simple objects method has been used. The 3D geometry of the element is created in create part tab by taking modelling space and element type. The cross section (125 mm thick and 250 mm deep) of the concrete beam was created and the beam was extruded in the direction of length. By adopting the prescribed procedure to create elements, geometrical model of beam specimens created in ABAQUS is depicted in Figure 3 (a). For the simplicity of assembling the elements, datum planes were created using create partition cell tool.

The steel reinforcement (both main steel and stirrups) was modelled as wire elements in ABAQUS as per the experimental reinforcement detailing. Elements of reinforcement i.e., tension bar, top bar and stirrups were created individually under the create part section and assigned a cross section area of these wire elements as a truss element. These elements were assembled and rearranged using translate, rotate and linear pattern instance tool in the assembly section by providing required spacing, effective covers and other details according to reinforcement assembly. The 8 mm diameter bar was used as web reinforcement and top bars in the beams whereas the 12 mm diameter bar was used as a main steel provided at the bottom. The nominal top reinforcement in the compression zone was curtailed in order to achieve the effect of singly reinforced section in predefined region of pure bending as described earlier. The reinforcement cage similar to actually used in the beam is modelled which is shown in Figure 3(b).



(a) Geometrical modelling of beams and supports

(b) Configuration of reinforcement

Figure 3. Geometry of the beam specimen created in ABAQUS

3. 2. Material Definition In the FE analysis part, the brittle-cracking model available in ABAQUS is employed as a material model. This yields better results when the behaviour of concrete material is governed by tensile cracking. The behaviour in compression is also idealised to be linear before cracking. In order to detect the crack initiation and propagation, a simple Rankine yield criterion has been utilised. According to Rankine yield criterion, the material starts cracking when resultant principal stress crosses the concrete tensile-strength. It is obvious that the crack surface is perpendicular to the major principal tensile stress. Subsequently other developed cracks are normal to the existing crack at the same location. Unlike other models, in this model, crack closing and reopening is allowed. Crack gets bridged as soon as the resultant principal stress becomes compressive after redistribution of stress. Moreover, it uses smeared crack model philosophy to characterize the non-ductile response of concrete.

The Brittle-cracking model includes two modes of failures as follows: 1) Mode-I based on tension-stiffening and Mode-II is on the basis of shear-retention. In strain-softening the stress linearly goes on decreasing to zero. As per the model, in the post-peak region, the strain is 10 times that of failure strain when the stress resumes to zero value. The crack initiation is controlled by Mode-I while the post-peak cracks are governed by both the modes. To model shear-behaviour, the post-cracking shear-modulus is defined in terms of the fractions of non-cracked shear-modulus. The model treats shear-retention in terms post-cracking shear-stiffness which is defined in terms of opening strain normal to crack.

3. 2. 1. Concrete ABAQUS offers freedom to user to define the material of practical relevance. It defines the concrete behaviour in terms of Concrete

Damage Plasticity (CDP) model. The other input parameters should be evaluated in the laboratory or idealised values reported in the literature may be used in absence of data. However, the real values are expected to use as an input in order to get accurate analysis.

The stress-strain relation of concrete used in the numerical-analysis should to be determined by testing the specimen in the laboratory. Figure 4 depicts the window to enter user defined material definition in the form of compression test stress-strain data and damage parameter on the basis of inelastic strain. Likewise, tensile test stress-strain data and damage parameter of the material model can be fed up to define the CDP model for concrete.

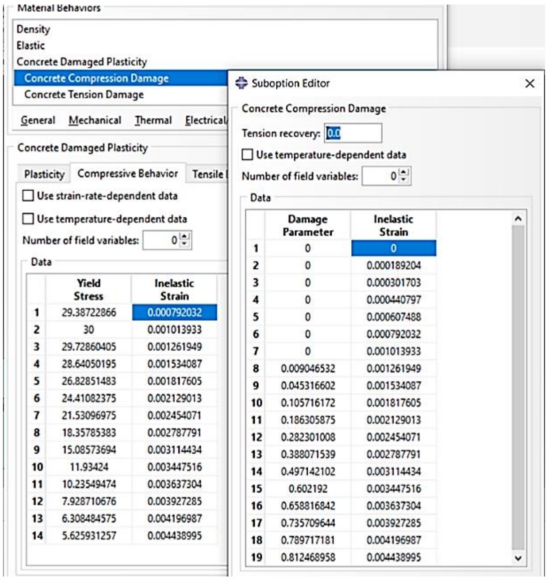
In this investigation, typical constitutive model for RAC was proposed by Suryawanshi et al. [11] which is used to define the concrete behaviour as follows:

$$\bar{\sigma} = a(\bar{\varepsilon}) + b(\bar{\varepsilon})^2 + c(\bar{\varepsilon})^3 + d(\bar{\varepsilon})^4 \quad (1)$$

where, $\bar{\sigma}$ is the normalized stress, $\bar{\varepsilon}$ is the normalized strain. Constants a, b, c and d were determined by regression analysis of test data. Constant a has definite meaning and may be defined in terms of percentage replacement of NA. Other coefficients b, c and d were expressed in relation of a.

3. 2. 2. Steel Reinforcement

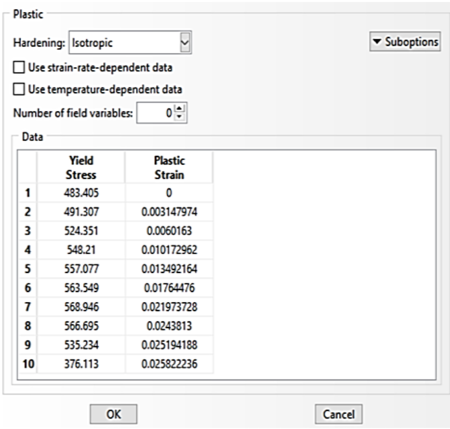
As discussed in the preceding sections, ABAQUS allow users to enter the stress-strain relationship of steel as input data so that the software can effectively simulate the behaviour of reinforcement steel. Figure 5 shows the appearance of dialogue box after entering the measured stress-strain values. It should be noted that, the ABAQUS accepts only inelastic strain values and corresponding stress values. The value of inelastic strain is determined as a difference of total strain and elastic strain.



	Yield Stress	Inelastic Strain
1	29.38722866	0.000792032
2	30	0.001013933
3	29.72860405	0.001261949
4	28.64050195	0.001534087
5	26.82851483	0.001817605
6	24.41082375	0.002129013
7	21.53096975	0.002454071
8	18.35785383	0.002787791
9	15.08573694	0.003114434
10	11.93424	0.003447516
11	10.23549474	0.003637304
12	7.928710676	0.003927285
13	6.308484575	0.004196987
14	5.625931257	0.004438995

	Damage Parameter	Inelastic Strain
1	0	0
2	0	0.000189204
3	0	0.000301703
4	0	0.000440797
5	0	0.000607488
6	0	0.000792032
7	0	0.001013933
8	0.009046532	0.001261949
9	0.045316602	0.001534087
10	0.105716172	0.001817605
11	0.186305875	0.002129013
12	0.282301008	0.002454071
13	0.388071539	0.002787791
14	0.497142102	0.003114434
15	0.602192	0.003447516
16	0.658816842	0.003637304
17	0.735709644	0.003927285
18	0.789717181	0.004196987
19	0.812468958	0.004438995

Figure 4. Details of stress-strain relations for concrete as an input parameter



	Yield Stress	Plastic Strain
1	483.405	0
2	491.307	0.003147974
3	524.351	0.0060163
4	548.21	0.010172962
5	557.077	0.013492164
6	563.549	0.01764476
7	568.946	0.021973728
8	566.695	0.0243813
9	535.234	0.025194188
10	376.113	0.025822236

Figure 5. Details of measured stress-strain relations for reinforcement as an input parameter

3. 3. Modeling of Support and Load Points

Unlike few FEA packages, ABAQUS allows to model and simulate curved elements like steel rollers used at loading points and supporting points through perfect contact as illustrated in Figure 6. The force was applied to beam by displacement controlled strategy as per prescribed deformation rate at the centre-point of the top surface of the spreader beam. The supports, in the form of two steel rollers used in experiments were modelled by appropriate boundary conditions on a line of contact. The supports were assumed as a rigid body and restricted to a predefined point as a reference. The movement reference point in vertical direction was restrained. Similarly, the steel rollers were modelled beneath the spreader beam used to apply load on the RC beam. The monitoring point to record the magnitude of applied load was placed at the centre-point of top surface of spreader beam. The position of the deflection monitors was the point where the LVDT was mounted in the prototype test.

For the structured meshes, the ABAQUS solver allows the usage of first-order hexahedral components; however, for unstructured meshes it permits the use of both first and second-order tetrahedral elements. 8-noded 3D hexahedral elements in the form of bricks (C3D8I) were employed in this investigation. The behaviour of traditional 8-noded elements is prohibited from being over rigid in bending by internally incompatible deformation modes, besides the normal degrees of freedom for displacement. The mesh being utilised for the concrete has an impact on how these components are implemented in the FE model. This work made use of the 3D linear truss (T3D2) element type with a mesh size of 10 mm. The geometry of a simulated beam with produced mesh elements is shown in Figure 6.

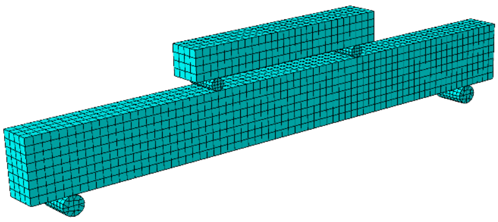


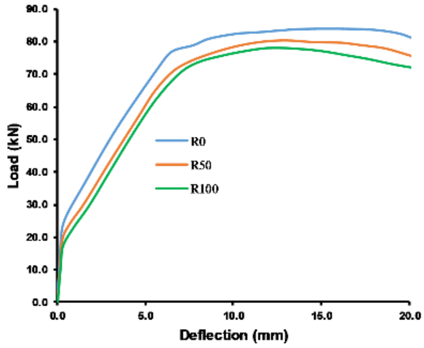
Figure 6. Finite element mesh of assembly

4. RESULT AND DISCUSSION

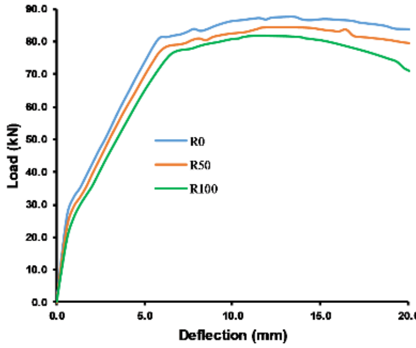
4. 1. Load Deflection Behavior The results of beam tests are compiled in Table 2 for reference and compared against results obtained from the ABAQUS analysis. It is clearly seen that the load carrying capacity of the beam when analysed by ABAQUS software is found in the close range to that of experimentally obtained results. It has been observed that the load carrying capacity of the RAC-beam is marginally lesser and slightly higher deflections than that of the NAC-beam. The ABAQUS analysis also indicate similar trend of reduction in load carrying capacity and increased deflections on higher replacement levels. Recent literature review on experimental flexure tests performed by Seara-Paz et al. [20] and Pradhan et al. [8] also agree that load carrying capacity of RAC-beam is lesser and shows higher deflection compared to NAC-beam. This may be attributed to the reduction of modulus of elasticity of concrete corresponding to a higher degree of replacement of NA [21].

The comparison of experimentally obtained load-deflection curves for beam specimens R00, R50 and R100 respectively are shown in Figure 7(a). A side-by-side comparison of ABAQUS analysis load-deflection curves for each beam is also presented in Figure 7(b). The trends of load-deformation characteristics in both the analysis are similar. The RAC beams had a lesser cracking load than the NAC beams due to the presence of two types of interfacial transition zones (ITZ) [22]. The ITZ between residual mortar and virgin aggregate in and the ITZ between new mortar and residual mortar. On the contrary, the NAC has one ITZ (between fresh mortar and virgin aggregate). Moreover, the RAC beams exhibited lower stiffness after the cracking load, which may be attributed to the RCA-concrete having comparatively lower modulus of elasticity to that of the NAC [23].

Figure 8(a), (b) and (c) reveals load-deflection relationships of tested beam specimens correspond to different RCA replacement levels, 0.0, 50 and 100%. The load-deflection relationships generated by ABAQUS software are also shown in Figure 8(a), (b) and (c). After cracking, each specimen behaved almost linearly until the tension bar began to yield. Each specimen thereafter

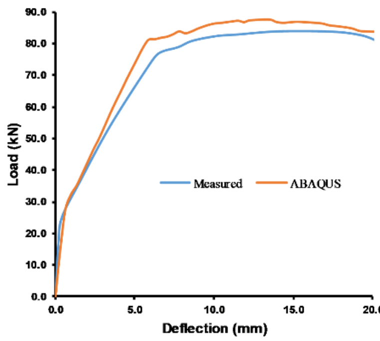


(a) Measured load-deflection relationship

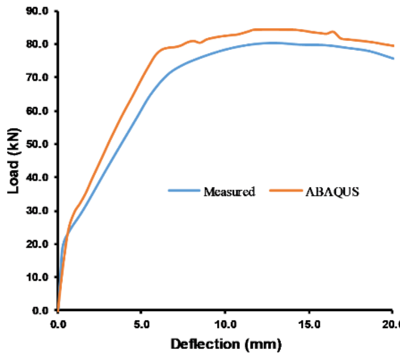


(b) Predicted load-deflection relationship

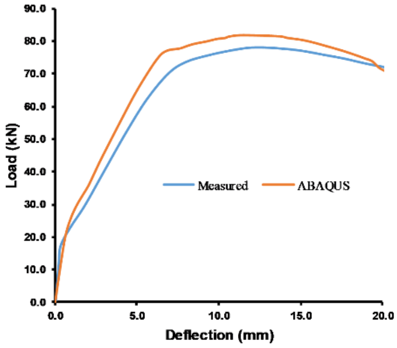
Figure 7. Comprehensive comparison of trends of measured and predicted load-deflection relationships



(a) Beam R00



(b) Beam R50



(c) Beam R100

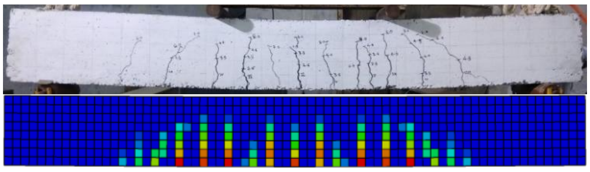
Figure 8. Comparison of measured and predicted load-deflection relationships of various beams

exhibited nonlinear behavior until it reached its failure load. The beams then reached a ductile plateau which is typical behaviour of RCC flexural member. After enough rotation of the developed plastic-hinge, extreme stresses are developed in the compression zone of the specimens, culminating in crushing failure.

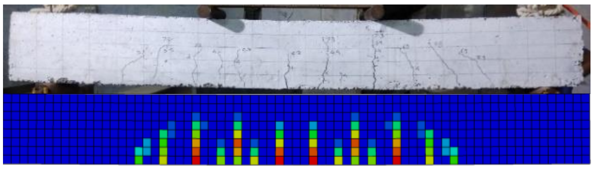
4. 2. Cracking Behavior of RCA-Concrete Beam

The cracking behavior of the beams in terms of the number, the orientation, and the extent of the cracks, was monitored throughout the loading history. The first crack started forming from the soffit of beam in the mid-span region, the region of maximum bending moment. The first crack occurred at 25 kN in R00-beam whereas the FEA simulation revealed it at 27.32 kN. Similarly, the first crack formed at 17.21 kN in R100-beam and at 25.78 kN in simulated beam. All beam specimens containing RCA-concrete showed the tendency of first crack formation comparatively at lower load to that of beam containing NAC. With increase in applied load, additional flexural cracks were formed between the loading point and the support points. All these cracks propagated towards the compression zone revealed the typical crack-pattern of inclined flexure-shear cracks. It is clearly seen that the R00-beams has the least number but prominent cracks (Figure 9), whereas the R100-beam comparatively has a greater number of minor cracks. The findings of this investigation were in good agreement with observations of past study [8], in which the cracks in the RCA beams were closely spaced than in the NA beams. This might be due to the weakened interfacial transition zone of RCA between the new mortar and the old attached mortar. Besides the experientially observed cracking patterns, the bands of principal tensile strains revealed in ABAQUS analysis also presented in Figure 9.

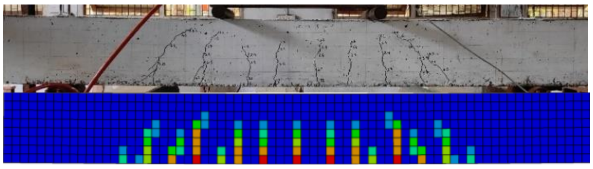
On the contrary, it generates the bands of principal tensile strains [24]. The formation of tensile strain bands with specific colour to represent certain magnitude of



R0



R50



R100

Figure 9. Comparison of observed creack patterns with ABAQUS simulated principal tensile strain profiles

strains can be compared with the actual crack patterns observed during experiments. The comparison of crack patterns of beams with different replacement levels of RCA is shown in Figure 9. along with the principal tensile strain patterns generated by ABAQUS. The trend of the principal tensile strain patterns generated by ABAQUS is comparable with the experimentally observed crack patterns.

5. CONCLUSIONS

In this comparative study, the flexural member was numerically investigated and compared with the results of experimental study. Based on the experimental findings and results of numerical analysis, the following conclusions have been drawn.

1. The comparison of ABAQUS results and experimental observations revealed no major differences in the load carrying capacities of the beams. The trend of reduction in load carrying capacity and increasing mid-point deflections with increased replacement level in both the investigations are similar.
2. The load deformation characteristics revealed by ABAQUS simulation is significantly in match with that of experimentally measured load-deformation relationships. Thus indicating the importance of well define material definitions in terms of measured stress-strain relations on yield of numerical simulations.
3. Unlike other FEA packages, ABAQUS does not generate crack patterns. However, the crack patterns observed during experiments can be correlated with

the principal tensile strain profiles generated through numerical simulation. The cracking patterns and principal tensile strain profiles are found comparable.

4. Besides, correct material definitions, other input parameters in terms of index properties of materials has a control on the quality of simulation.
5. Geometric definition, well defined support conditions and appropriate selections of finite elements are the major factor influencing the outcomes of FEA analysis.

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Persian Abstract

چکیده

دقت پیش‌بینی بسته‌های مبتنی بر المان محدود (FE) به طور گسترده بر اساس سازگاری رویه‌های عددی غیرخطی اتخاذ شده و مدل‌های مواد گنجانده شده است. با این حال، روش معمول برای تعریف مواد بتن برای بتن های حاوی مواد جایگزین به جای مواد بتن معمولی قابل اجرا نیست. بنابراین، در این کار، از تعریف مناسب مواد از نظر روابط تنش-کرنش برای شبیه‌سازی کار تجربی تیرهای RC حاوی بخش‌های درشت‌تر از سنگدانه‌های بتن بازیافتی (RCA) استفاده شده است. کل کار در دو مرحله انجام شده است. یک کار آزمایشی و شبیه سازی کار آزمایشی با استفاده از بسته FEA، ABAQUS. در بخش آزمایشی، سه نمونه تیر با مقیاس کامل از طریق بارگذاری یکنواخت چهار نقطه‌ای برای شکست مورد آزمایش قرار گرفتند. سطح جایگزینی سنگدانه های درشت طبیعی با جایگزینی مستقیم ۰.۰، ۵۰ و ۱۰۰ درصد در نظر گرفته شد. در مرحله شبیه سازی، علاوه بر خواص آزمایشگاهی ارزیابی شده مانند تنش فشاری، تنش کششی و مدول الاستیک، رابطه تنش-کرنش اندازه گیری شده برای فولاد تقویت کننده و رابطه سازنده برای بتن سنگدانه های بازیافتی (RAC) گزارش شده در ادبیات به عنوان ورودی در نظر گرفته شده است. . روابط تنش-کرنش RAC انتخاب شده از ادبیات به عنوان مدل تعریف شده توسط کاربر در نظر گرفته شده است. علاوه بر استحکام، قابلیت سرویس از نظر انحراف، الگوهای ترک و ویژگی‌های تغییر شکل بار تیرهای شبیه‌سازی شده بررسی و با نمونه‌های تیر آزمایش‌شده آزمایشگاهی مقایسه شده است.