Experimental study and 3D nonlinear FEA of shear capacity for lightweight concrete beams

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This paper presents results of experimental study on shear capacity of artificial lightweight reinforced concrete beams without shear reinforcement. 3D nonlinear computational simulation was used to investigate shear failure process and capacity of the beams. Nominal shear strengths of the sand lightweight (2150 kg/m³) and the semi-lightweight (2000 kg/m³) concrete beams, decreased by about 10% and 20% respectively compared to that of normal weight concrete beams. Using the same set of material models, it was possible to capture the brittle failure behavior and predict ultimate shear capacity of RC beams with reasonable accuracy. This study also confirmed the effectiveness of longitudinal reinforcement along the side of a beam's cross section.

Key Words : Lightweight Concrete, Shear Capacity, Smeared Crack Model, Nonlinear Finite Element Analysis

1. Introduction

Lightweight aggregate concrete has been used in American and European highway bridges for many years. Experience in Japan where LWA concrete was applied extensively in elevated expressways where space has been restricted and ground conditions are poor, suggests the advantages of the concrete 1). The use of LWA concrete has several merits such as: (1) Possible lower inertia forces acting on a structure, (2) Possible lower member forces acting on a foundation. Therefore, it reduces dimension of the foundation, especially in the area of poor ground conditions, (3) The size of structure in general could also be reduced, (4) Since smaller, lighter transportation and machineries can be used, shorter construction time is expected. In general, proper use of the LWA concrete could gain lower total construction cost. Previous study ²⁾ showed that LWA concrete performs equally to normal weight concrete in the case of flexural loading. If the material is acceptable for shear design, it is very desirable for a variety of application such as pier and deck in highway bridges, slab floor and joints in high-rise building construction and offshore structures.

The main concern of the LWA RC members is the high brittleness of the concrete both in tension and compression. The low tensile strength of LWA concrete is the major factor contributing to reduction of the shear capacity of a RC member. Current Japan standard specification for concrete³⁾ requires that tensile, bonding strength as well as nominal shear strength by "concrete mechanism"" of the "all lightweight" (both fine and coarse aggregates are lightweight) concrete is 70% of that of normal concrete of the same compressive strength.

However, it is well known that LWA concrete can be made using different combinations of lightweight and normal weight aggregates. For example, the "semi-lightweight" concrete made with lightweight coarse aggregate and natural sand, while the "sand lightweight" concrete made with lightweight fine aggregate and normal weight coarse aggregate. It is also possible to mix lightweight and normal weight coarse aggregate to make a lightweight concrete with certain density. Since various types of LWA concrete exists, 30% reduction of the nominal shear strength required by the Standard³⁾ is limited in use. There is substantial evidence that shear strength of LWA concrete depends on its density ⁴⁾.

Although much has been learned about the shear failure, the question of physical mechanism of shear failure in reinforced concrete beams, still remains far from being settled. One of the major difficulties in developing theoretical expression for shearing strength of RC beams is primarily

Name	Symbol	Туре	Notes				
Cement	C	Normal Portland cement	Density 3.16(g/cm ³)				
Fine aggregate	S	Natural sand	Dry density 2.60(g/cm ³)				
		Lightweight (Asanolite)	Dry density 1.90(g/cm ³), absorp-				
			tion 20.2 %				
Coarse aggregate	G	Natural crushed rock	Dry density 2.63(g/cm ³)				
		Lightweight (Asanolite)	Dry density 1.58(g/cm ³), absorp-				
			tion 28.9 %				
Admixture	LS	Limestone powder	Density 2.70(g/cm ³)				
Admixture	SP	High performance water re-	SP8N				
		ducing agent					
	AF	Antifoam agent	Micro-air 404				
	MC	Vicious agent	90EMP-15000				

 Table 1
 Materials for concrete mixture in double shear test

 Table 2 Mixture proportion for shear test

Beams	W/C	s/a	Weight per unit volume (kg/m ³)								
Name	(%)	(%)	W	C	LS	SN	SL	GN	GL	SP C	AF
NSNG25-3	83			199	190					2.189	0.398
NSNG40-3	60	48	165	247	126	879	-	960	-	3.705	0.494
NSNG55-3	47	1		349	62	1				6.282	0.698
LSNG25-3	72			228	165					2.508	0.456
LSNG40-3	51	48	165	324	83	-	653	960	-	4.86	0.648
LSNG55-3	39			420	0					7.56	0.84
NSLG40-3	56			293	109					3.223	0.586
NSLG40-3P	56	48	165	293	109	879	-	-	584	3.223	0.586
NSLG55-3	39	1		421	0	1				5.473	0.842

due to the indeterminacy of the internal force system of a cracked concrete at ultimate stage. RC beams fail in quite complicated manner in the ultimate stage involving evolution of distributed damages and localized fracture, which causes the size effect. That is why all of the equations for prediction of shear capacity are empirical or semiempirical. Recent successful development of finite element method applied to nonlinear problem of reinforced concrete offers another opportunity to deal with the problem of shear failure phenomenon. There are three major approaches for describing cracking in finite element analysis. They are (1) smeared crack models, (2) embedded crack models and (3) discrete crack models. In smeared crack formulation, the crack is distributed over finite zone and an 'equivalent' tensile strain is used to define softening. This approach is the most popular since it is easily implemented in FEA.

In this study, we focus on the shear capacity of beams made with two types of artificial lightweight aggregate concrete: the sand lightweight (SLW) concrete and the semi-lightweight (SMLW) concrete. Though most studies concern the SMLW concrete, the SLW concrete has certain better characteristics. It is nearly 15% lighter than normal concrete. It is considerable higher tensile strength and elastic modulus compared to that of SMLW concrete. Another objective of this study is to numerically investigate the behavior of beams under shear forces. It utilizes three-dimensional (3D) nonlinear finite element analysis (FEA). Advantage of 3D nonlinear FEA is that it is possible not only to predict shear capacity but also to capture deformation behavior of beams from zero load to complete failure. It is also interested to know if current available constitutive models and failure criteria are applicable for different types of LWA concrete.

2. Experiment program

2.1 Materials and concrete mix proportion

Materials for concrete mixture are presented in Table 1. Coarse and fine lightweight aggregates are made from expanded shale with oven dry density of 1.9g/cm³ and 1.58g/cm³ respectively. The maximum aggregate size is 15mm. Selection of mix proportions for concrete specimens is presented in Table 2. Three different Water/Cement (W/C) ratios were used for each type of concrete mixtures. This aims to obtain three target strengths: 25, 40 and 55 N/mm². Along with each batch a number of standard cylindrical specimens, referred hereafter as control cylinders, were also cast for testing of concrete fundamental properties. In order to avoid escape of moisture all beams and their respective control cylinders were folded by wet cloths then covered using vinyl sheets until the test day. Deformed bars SD345 were used as longitudinal reinforcement. The average yield strength of coupon



Fig. 1 Beam and load configuration (unit mm)

No.	Name	$f_{c}^{'}$	a/d	ρ
		(N/mm^2)		(%)
1	N25-3	24.40	3	1.5
2	N40-3	41.70	3	1.5
3	N55-3	52.80	3	1.5
4	SLW25-3	25.60	3	1.5
5	SLW40-3	46.40	3	1.5
6	SLW55-3	51.00	3	1.5
7	SMLW40-3	37.80	3	1.5
8	SMLW40-3P	43.00	3	1.0
9	SMLW55-3	53.80	3	1.5

 Table 3 Details of tested beams

specimens was 378N/mm².

2.2 Specimen details and loading method

A total of 9 shear-dominated reinforced concrete beams without web reinforcement were tested. The test variables were concrete strength and types of concrete. There were two types of LWA concrete in this experiment. The SLW concrete and the SMLW concrete. For comparison purpose normal weight concrete beams were also tested . Ta**ble** 3 shows data of tested beams, where f'_c , a/d and ρ are concrete strength, shear span ratio and steel ratio of all bars in tension zone. For each type of concrete there are three beams with target concrete strengths of 25, 40 and 55N/mm² respectively. Beam number 7 and beam number 8 have the same target strength but different longitudinal bars ratio. These two beams were designed to investigate the effect of longitudinal reinforcement along the side of cross section, hereafter referred as side reinforcement. Fig.1 shows details reinforcement and loading configuration of a beam. The beam has 200×200mm cross section and 1600mm of total length. Actual shear span is 516mm and section effective depth is 172mm. This makes shear span to depth ratio equal three for all beams in the experiment. Except the case of beam SMLW40-3P, all other beams are longitudinally reinforced with 16 bars SD345-D10 around the perimeter of a cross section. To confirm the effect of side reinforcement, SMLW40-3P is reinforced with only longitudinal bars in the tension and compression zone. The effectiveness of side reinforcement, which was reported by Tsuchiya et al.⁵), is due to

distributed effect of diagonal crack. Crack evolutions at beam surface and internal sections are very different and can only captured using 3D analysis.

Since specimens resemble a case of bridge pier, one point loading was selected. Loading was monitored using a load cell placed under hydraulic jack and the midspan deflection was measured using high precision LVDT (Linear voltage differential transducer) at the middle of bottom face of beam. Strain development in longitudinal reinforcing bars was monitored at three different sections (see **Fig.1**) using steel strain gages embedded in specimen before casting. In addition, a surface strain gage was glued next to loading plate to measure concrete strain in compression zone near the load point. Loading was forcecontrol monotonic. Cracks evolution was sketched for different step of loading.

3. Experiment results

3.1 Critical diagonal crack characteristics

When applied load increases, the first crack occurred in central portion of a beam due to bending stress following by growth of other vertical flexural cracks, originated from bottom of the beam, in the shear span. At certain load level, crack failure became stable and number of cracks stopped to increase. Vertical bending cracks then started to bend toward the load point. Though a number of flexural cracks occurred in the span, maximum flexural crack width was small. From our observation the maximum crack width was in a range from 0.06mm to 0.08mm. The small flexural crack width indicated low bending stress in the middle of the beam. Critical diagonal crack developed, after the onset of near-by flexural cracks, close to the support. This predominant crack propagated abruptly toward the load point, crossed other flexural cracks, penetrated deeply into the compression zone causing sudden loss of beam bearing capacity. At this point, in some beams, loading turned to unloading phase with clear drop of shear force. But then a beam regained its load resistance with load increased by extra amount to maximum ultimate value before complete shear failure. In the other beams there was no recover of beam resistance, the beam instantaneously failed because of the critical diagonal crack.

Fig.2 show crack patterns of all damaged beams. It is clear that the number of flexural cracks in the shear span

of normal weight concrete is larger than that of LWA concrete beams. Extensive development of flexural cracks indicates better bonding between reinforcing bars and concrete. Most of the beams, except SMLW40-3P, show pattern of diagonal distributed damage where there is more than one diagonal crack occurred together with falling-off of cover concrete along diagonal cracks. This effect is due to the side reinforcement and it is very notable in medium and high strength concrete beams. Crack pattern of the SMLW40-3P is somewhat different from other beams with single more curvy diagonal crack.

Inclining angles of diagonal cracks (θ) with respect to member axis were different for different concrete strengths. High strength concrete beams had these angles in a range from 30^0 to 35^0 , while the angle in medium and low strength concrete beams was from 25^0 to 30^0 . The (θ) affects the effectiveness of web reinforcement. It is well known that shear force resisted by web reinforcement V_s is proportional to $\cot \theta$. That is the larger θ is the lower V_s is. It appeared that high strength concrete requires more web reinforcement.

3.2 Diagonal crack load

Shear capacity at critical diagonal crack of a beam was detected based on load-mid span deflection curve. In many cases there was clear indication of occurrence of diagonal cracks, where load suddenly decreased (see Fig.6). However in other cases this point was not so obvious. In these cases the diagonal crack load was determined by visual inspection during specimen's loading. There was load recovery after the first critical diagonal crack as reported by many other researchers, however sudden decrease of load at the first critical diagonal crack could lead to collapse in a real structure. A prediction of shear capacity at diagonal crack, therefore, is a central objective of shear studies. Based on a vast number of shear tests around the world, Niwa et al.⁶⁾ proposed an equation for the shear capacity prediction of a RC beam without web reinforcement. The equation is said to predict shear capacity of normal strength normal weight concrete beams very closely⁴⁾⁵⁾. Niwa's equation contains size effect $(\sqrt[4]{1000/d})$, which has the following form:

$$\frac{V_c}{bd} = 0.2 \sqrt[3]{f'_c} \sqrt[3]{100p} \sqrt[4]{1000/d} \left(0.75 + \frac{1.4}{a/d} \right) \quad (1)$$

Provided that $\sqrt[3]{f'_c} \leq 3.6$.

Where, V_c is Diagonal crack load (N), f'_c is concrete compressive strength (N/mm²), p is the longitudinal steel bars ratio (%), b is section width (mm), d is section effective depth (mm), a is shear span (mm) and $\tau_c = \frac{V_c}{bd}$ is nominal shear strength.

Equation 1 was used to calculate diagonal crack loads. Summary of this calculation as well as related experimental results are given in **Table** 4. As given in the table, the ratios of experimental diagonal crack capacity to calculated one using Niwa's equation $\left(\frac{V_c - exp}{V_c - cal}\right)$ are



Fig. 2 Crack patterns

lower for lighter weight concrete. This indicates dependence of shear capacity to unit weight of concrete as reported elsewhere⁴⁾⁷⁾. **Fig.**3 shows relation between this ratio $(\frac{V_c - exp}{V_c - cal})$ and concrete density. It has been found that shear capacity of sand lightweight (SLW) concrete beam is less than that of normal concrete beam by about 10%, whereas reduction of semi-lightweight (SMLW) concrete beam is approximately 20%. In addition, if we compare SMLW40-3 to SMLW40-3P using $(\frac{V_c - exp}{V_c - cal})$ ratio then relatively the former has shear capacity higher than that of the later by 26% (1.19/0.94 \approx 1.26). From **Equation** 1 it is found that, a beam with steel ratio of 1.5% has capac-

No.	Name	f_c'	f_t	E_c	V_{c-exp}	τ_{c-exp}	V_{c-cal}	$\frac{V_{c-exp}}{V_{c-cal}}$	V_{u-exp}	V_{u-FEA}	$\frac{V_{u-exp}}{V_{c-exp}}$	$\frac{V_{u-exp}}{V_{u-FEA}}$
											*	
1	N25-3	24.4	2.2	25.0	57.6	1.67	42.7	1.35	57.7	57.4	1.00	1.00
2	N40-3	41.7	3.2	30.9	75.5	2.19	51.0	1.48	77.8	78.9	1.03	0.99
3	N55-3	52.8	3.6	30.6	77.5	2.28	55.2	1.42	77.8	88.5	0.99	0.88
4	SLW25-3	25.6	2.2	21.9	55.5	1.61	43.4	1.28	59.7	56.5	1.08	1.06
5	SLW40-3	46.4	3.2	24.8	65.0	1.89	52.9	1.23	72.5	77.4	1.12	0.94
6	SLW55-3	51.0	3.4	24.9	71.0	2.06	54.6	1.30	94.6	81.0	1.33	1.17
7	SMLW40-3	37.8	2.6	19.1	59.0	1.72	49.4	1.19	66.2	65.9	1.12	1.01
8	SMLW40-3P	43.0	2.4	18.8	43.0	1.25	45.5	0.94	57.5	58.0	1.34	0.99
9	SMLW55-3	53.8	3.2	22.1	65.0	1.89	55.5	1.17	80.6	80.0	1.24	1.01

Table 4 Experimental and Analytical Results

 f'_c : Compressive strength (N/mm^2) , f_t : Tensile strength (N/mm^2) , E_c : Elastic modulus (kN/mm^2) , V_{c-exp} : Exp. crack load(kN) τ_{c-exp} : Experimental nominal strength (N/mm^2) , V_{c-cal} : Crack load by Equation 1(kN)

 V_{u-exp} : Experimental ultimate(maximum) shear load(kN), V_{u-FEA} : Ultimate load by Finite Element Analysis (kN)



Fig. 3 Shear capacity ratio vs. unit weight

ity14% higher than that of the same beam with only 1.0% steel ratio. Since the only differences betwwen SMLW40-3 and SMLW40-3P are steel ratio and rebars arrangement, it is alsmost certain that 12% improvement in shear capacity of SMLW40-3 is due to the effect of side reinforcement. Table 4 also gives the ratio of experimental maximum shear to diagonal crack capacity $\left(\frac{V_{u-exp}}{V_{c-exp}}\right)$. In six cases this ratio is close to one, indicating that loss of load bearing ability occurred right after formation of the first diagonal crack. Three other beams (SMLW40-3P, SLW55-3 and SMLW55-3) have this ratio some what higher. In these beams after load reduction because of the first diagonal crack occurred in one shear span, a stable bearing mechanism attained and formation of the other diagonal crack in the opposite shear span (see Fig.2) has been found. Loss of load bearing ability in these beam has occurred only after diagonal cracks penetrated compression zone. Failure mode of beams was judged using strain gage attached to concrete surface compression zone. It has been found that all beams failed in diagonal tension with high strain in compression zone but less than ultimate value. Main bars of SLW55-3 started to yield right at the peak load, however main bars of other beams were well bellow the yield limit.

Empirical approach to predict shear capacity of a RC

beam, e.g. **Equation** 1, is practically useful. However it has no physical meaning related to load bearing mechanism of the beam. This limits the scope of application of any formula for shear capacity prediction. If parameter of a beam is "out of range " of experimental data the prediction is then unreliable. Moreover, dependence of shear capacity of lightweight concrete beams on the concrete density, which has been found in this study as well as others ⁴), has only practical meaning. There is also no physical link between concrete density and shear capacity of a beam.

In fact concrete strengths and modulus of elasticity have direct influence to the shear capacity and deformability a beam. For example, tensile strength is dominant factor affects the formation of diagonal crack in a beam failed in diagonal tension or compressive strength governs the ultimate capacity of a beam failed in shear compression mode. The reason why we have found dependence between shear capacity and concrete density is because there is dependence between concrete tensile strength and concrete density as reported by Funahashi⁴⁾. Finite element analysis is an ideal approach relating material parameters to actual load bearing mechanism of a beam.

4. Finite Element Analysis

In this study, concrete behavior and cracks development are described using multi-directional smeared crack model. Computer code for nonlinear finite element analysis (FINAL) was developed by the Obayashi Corporation. Using this software program we attempt to check if currently available constitutive models for concrete can be applied to predict shear behavior of lightweight concrete beams. Material parameters such as compressive, tensile strength and modulus of elasticity, which were obtained from experiment, were taken as input data for the analysis.

4.1 Constitutive model for steel bars

Bilinear model was used to model behavior of steel bars. Parameters for the model such as steel modulus, yield strength and poisson ratio were obtained from tests.

4.2 Concrete in compression

Modified Ahmad stress-strain relationship was used in this study for concrete constitutive model in compression. The model was originally proposed by Ahmad⁸⁾ but later modified by Naganuma⁹⁾ to improve descending branch of stress-strain curve. The model used common approach to relate multidimensional stress and strain relationship to a pair of quantities, namely, the effective stress and effective strain, such that results obtained following different loading paths can all be correlated by means of the equivalent uniaxial stress-strain curve. The equation of the modified Ahmad model has the following form:

$$\sigma = \frac{\left[\left(AX + (D-1)X^2 \right) \right] \sigma_p}{1 + (A-2)X + DX^2}$$
(2)

For ascending branch ($\epsilon \leq \epsilon_p$):

$$X = \frac{\epsilon}{\epsilon_p}; D = \frac{200}{\sigma_B} - \left(\frac{E_B}{E_p} - 1\right); E_B = \frac{\sigma_B}{\epsilon_B}$$
$$A = \frac{E_0}{E_p}; E_0 = \left(1.14\sqrt{\sigma_B} + 5.82\right) \times 10^4$$

For descending branch ($\epsilon_{i}\epsilon_{p}$):

$$X = \left(1 + \frac{\epsilon - \epsilon_p}{\epsilon_P}\right)^n$$
$$n = 0.9 + 3.4 \left(\frac{\sigma_B}{1000}\right)^2$$
$$D = 1 + 1800 \left(\frac{\sigma_p}{\sigma_B}\right)^2 / \sigma_P$$

Where, $\sigma_B, \epsilon_B, E_B$ are stress, strain and secant modulus at peak stress (strength) in uniaxial compression respectively. $\sigma_p, \epsilon_p, E_p$ are stress, strain and secant modulus at peak stress in multiaxial compression respectively.

4.3 Concrete in tension

When cracking of concrete take place, a smeared model is used to represent the discontinuous macrocrack behaviors. It is already known that the cracked concrete in reinforced concrete element can still carry some tensile stress in the direction normal to the crack, which stiffens reinforcing bars crossing the crack. The phenomenon is termed as tension stiffening. Tension stiffening effectiveness is characterized by the slop of the descending branch of tensile stress-strain curve. In this study a model proposed by Izumo et al.¹⁰⁾ was used for concrete stress-strain relationship in tension, which described by the following equation:

$$\frac{\sigma_t}{f_t} = \left(\frac{\epsilon_{cr}}{\epsilon_t}\right)^c \tag{3}$$

Where, f_t is tensile strength under biaxial loading, ϵ_t is average tensile strain in the direction perpendicular to crack. ϵ_{cr} is average tensile strain when crack occurred and c is parameter representing condition of bond between reinforcing bars and concrete. The lower value of c parameter the higher tension stiffening effect is. For example c=0.2 is applicable for RC member with welded mesh of deformed bars, c=0.4 is for member with normal mesh of deformed bars ¹⁰. In this experiment c=1.0 considering low ratio of reinforcement.

4.4 Failure criteria

The Ottosen four parameter model was selected for concrete failure criteria. According to Naganuma⁹⁾ the model performed quite well for concrete under low confinement which is the case of beam without web reinforcement. **Fig.**4 gives an outline of failure surface in principal stress space. The surface is an open surface, having the space diagonal as main axis, which is also referred as hydrostatic axis. Any plane perpendicular to hydrostatic axis will cross failure surface at deviatoric plane. The deviatoric plane has a convex shape, which is nearly triangular for low hydraulic pressure and nearly circular for very high pressure. Ottosen used three coordinates ξ , ρ and θ to describe the yield surface. Details of the model can be found in the work of Naganuma.



Fig. 4 Concrete yield surface in principal stress space



Fig. 5 Analytical model

4.5 Shear transfer mechanism

During the postcracking stage, the cracked reinforced concrete can still transfer shear forces through aggregate interlock or shear friction. This phenomenon is also termed as shear retention. However as pointed out by other researchers¹¹) for slender beams without web reinforcement shear interlock is almost ineffective. This shear resisting mechanism can only be effective if diagonal crack



Fig. 7 Failure conditions at maximum load

Section

Crushed

width is confined. Therefore shear interlocking was ignored in this study.

4.6 Finite element analytical model

Fig.5 shows a three dimensional finite element model for analysis of beam under one point loading. Some of main features of the model are as follow: a) Solid elements are used to model concrete, loading and supports plates as well as steel bars. Steel bars were modeled using solid element to closely describe the effect of dowel action; b) Concrete elements have common nodes with steel bars and plates. c) Incremental load then displacement was applied to middle of the top of loading plate. Load - mid span deflection was computed up to post failure.

4.7 Load-mid span deflection

Fig.6 shows experimental and computed load-mid span deflection of low, medium and high strength concrete beams respectively. Except the beam SLW55-3, all other beams load-deflection behavior were very closely predicted. Computed load-deflection curves show nearly the same stiffness with experimental curves up to maximum loads, and then a sharp decrease of computed load was obtained. This is the success simulation of the brittle shear failure in all beams under consideration. **Fig.**6(e) confirmed effect of the side reinforcement. SMLW40-3P, the beam with no side reinforcement shows lower ascending stiffness and decrease of maximum load compared to beam SMLW40-3. This figure also showed that, it is able to capture the main feature of the SMLW40-3P behavior

with similarity in shape of FEA curve with experimental one at the point of diagonal crack, though FEA diagonal crack load is a bit smaller. All computed curves, however, did not match experimental curves in the descending branch. This is because in the experiment, force-control loading was used. So right after the peak load has reached, strain energy in the loading device was released, causing impact-like displacement and inability to measure displacement. Only in deformation-control loading machine the post peak behavior of beam can be traced.

Table 4 gives ratio of experimental ultimate shear capacity to computed value using FEA. In many beams predicted ultimate shear capacity differed from experimental one by just only few percentages. The worst case of prediction is for SLW55-3. This beam showed somehow different behavior from others. After formation of the first diagonal crack, the beam sustained load bearing ability up to the point where the second diagonal crack occurred simultaneously with yielding of tensile rebars. Maximum load was much higher than computed value.

4.8 Damage distribution

Fig.7 shows examples of computed damage distribution at the maximum load. Two beams, namely SMLW40-3 and SMLW40-3P are selected here for representation. Computed and real crack distributions at beam surface are shown. The computed crack patterns have main features of real damages for both beams. Internal damage distributions of the beams together with principal stress distribution are shown at the middle section. From these pictures, one can find that stress distribution is quite different at different sections of a beam. Crack failure of the beams is three dimensional in nature.

5. Conclusions

The following conclusions are drawn from this study:

- Nominal shear strength of ALWA concrete beams depends on the unit weight of concretes. The sand lightweight concrete (density 2150kg/m³) and semilightweight concrete (density 2000kg/m³) beams have their shear capacity reduced by 10% and 20% compared to that of normal weight concrete.
- Using 3D nonlinear finite element analysis, with the same set of material models, it is possible to capture load-deflection behaviors up to the maximum load, brittle failure characteristic and very closely predict ultimate load of all beams.
- Computed crack failure distribution pattern has the main feature of the real damages. It is also found that stress distribution and damage condition at different longitudinal sections are different. That means damage of beam is three dimensional in nature.
- It is hoped that this study encouraged the use of 3D nonlinear FEA for analysis of shear capacity of member in unconventional structure subjected to predominant shear forces.

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