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STIFFNESS DEGRADATION OF RC BEAM BY DYNAMIC METHODS

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ABSTRACT

This paper investigates the reduction of stiffness, variation of flexural rigidity and nonlinear response of RC member to detect flexural cracks. The positive cyclic pseudo static load was applied stepwise to the specimen to induce damage. Flexural rigidity characteristics were studied by conducting free vibration test on RC beam at various stages. Vibration characteristics of each damage state were successfully identified to detect the relationship between damage levels and fundamental frequencies under various failure loads. Due to flexural cracks longitudinal bars may yield resulting in reduction in effective flexural rigidity and hence frequency. This yielding of reinforcement in longitudinal bars can be detected from change in natural frequency. The non-linearity was detected by checking the changes in the fundamental frequency during various stages of loading.

Keywords: Stiffness degradation; natural frequency; non-linearity; reinforced concrete beam.

1. INTRODUCTION

Reinforced concrete structures often lead to failure because of loss of the structural capacity of the members. Structural failure refers to the loss of structural integrity, which is the loss of the load-carrying capacity of a component or member within a structure, or of the structure itself. Structural failure is initiated when the material is stressed to its strength limit, thus causing fracture or excessive deformations. In a well-designed system, a localized failure should not cause immediate or even progressive collapse of the entire structure. Some of these damages are difficult to detect by visual inspection. Since reinforced concrete structures are nonlinear in behavior, the effects of change in natural frequencies can be used to detect damage on the RC beam. In the present study, damage assessment studies have been carried out on a reinforced concrete beam by evaluating the vibration characteristics with the changes in damage levels.

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Damage in concrete structures may be due to environmental conditions or due to overloading. The health of a structure over a certain period of its life need not be same as the health of virgin structure. The reason for such changes in the structural property may be due to (i) defective design, (ii) use of poor quality material and (iii) quality of construction especially with reference to reinforced concrete structures. When a reinforced concrete beam cracks due to various reasons its dynamic properties will change. The damage causes loss of stiffness which can lead to a decrease in natural frequencies [9]. Most of the dynamic tests conducted for health monitoring on actual structures utilize natural frequency to be the most convenient parameter to identify and quantify the damage.

2. LITERATURE REVIEW

Osman M. Ramadan et al [15] in their paper propose nonlinear analysis of RC beams with and without openings by comparing integrity analytically and experimentally and result were compared as beam strength, stiffness, deformed shape and cracking patterns. By adopting analytical methods we can save time and we can enhance the aspect of study, which were hard to conduct in experimental studies. By analyzing beams, the presence of opening decreases the initial and ultimate strength by 40% and 20% and at the same time stiffness were decreased by 20%. Sankar Jegadesh J S et al [24], in their paper deal with the non-linear analysis taken with softened membrane model (SSM) and MacGregor model. They incorporated the material properties and behavior characteristics of RC members which is used to obtain shear behavior. These analytical study based on five parameter plasticity failure surface due to William-Warne. The results were compared with load deflection curve of both analytical and experimental and predicts SMM give conservative result over MacGregor model.

V. B. Dawari et al.[25] carried out experimental and analytical study and found that non-linear flexural behavior of reinforced concrete beam depends on critical crack region, loads and deflection of various loading in RC beam. Comparison was made in ultimate load capacity of beams from experiment and analysis using numerical methods. Finite element models take accurate nonlinear flexural response of RC beam. It is found from load vs deflection curve that the result is more sensitive to mesh size, material properties and load increment. Vasudevan. G et al[19], studied the effect of shear reinforcements on flexural behavior, convergence criteria and impact of percentage of reinforcement. First cracking stage, steel yielding stage and at the ultimate stage lower convergence limits are to be used for accurate prediction of behavior. M. Al Amin Siddique [23] had investigated the material properties of over reinforced concrete beam with different characteristics in concrete and steel. In this paper load deformation behaviour of simply supported beam is more nonlinear and response divided in different stages. Newton-Rapson techinique had been used for the nonlinear equation and it has been observed that high strength concrete increases the strength and stiffness but decreases the ductility of the RC beam.

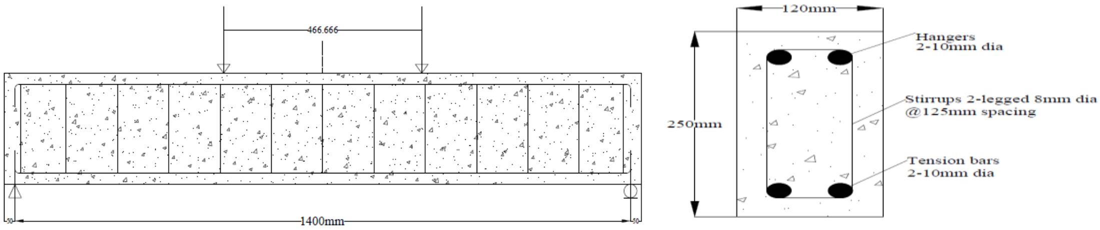
S.A. Neild et al [12] had investigated the changes in vibration characteristics to detect damages in reinforced concrete beams and these nonlinearities were detected by fundamental frequency during an impulse response with respect to time. The experimental data states that the strength of nonlinear behavior increases with damage and these damages were increase with 27% of the collapse load. Nonlinearities present in impact excitation vibrational signal, the time-frequency distribution of the signal were calculated at various levels of damage. Koen van den abele et al paper proposed the damages in different levels by static experimental modal analysis (EMA) to highlight the extreme sensitivity of their result to progressive micro crack damage in reinforced concrete structure and the structure is assumed to behave linearly. Static four point bending test EMA using mode curvature and bending stiffness shows that the local increase in damage in RC beams as a function of loading step. The nonlinearity is most effective indicator of cumulative micro damage with in a material and it helps to detect the early stages of detoriation due to micro cracking. Chen et al [5], proposed to detect damage in RC beam based on transient characteristics of nonlinear vibration by introducing fiber reinforced polymer sheet bonded externally on one beam. Both the beams are loaded statistically and dynamically to correlate the dynamic characteristics of the beam and the damage level. Both the beams are cracked at 36-45 kN. But the fiber beam reduce the deflection due to static load. The non linear parameter of the model identified from the experimental data increases the severity of damage. The aim of the work is to evaluate the detection of damage in RC elements where very high levels of structural integrity are required and compare the experimental and analytical studies with respect to damage in RC element.

3. BEAM SPECIMEN USED FOR THE PRESENT STUDY

RC beams were cast with concrete with a 28 days targeted cube compressive strength of 45 Mpa and tensile Strength of 4.74 Mpa. The beam specimen of size 1500 × 120 × 250 mm with an effective span of 1400mm is used for the study. Tension reinforcement bars of 2nos. 10mm diameter, hanger bars of 2nos. of 10mm diameter and shear reinforcement bars of 2-legged 8mm diameter @ 125mm spacing c/c were used. The clear cover of 25mm was used in experimental testing and effective cover of 30mm were used for Finite Element Modelling for the specimen. The beam specimen was tested under four point bending with loading at a distance 466mm (effective span (Le) /3) from either ends of the support, so as to have a constant moment's span of 468mm.

As per analytical part, the beam specimen was analyzed using ANSYS 14.5 and based on the material properties and multi-linear stress-strain curve for concrete given by IS456:2000 [1] and from the literature review [3-8]. All the other parameter which are not discussed, are taken as default values form ANSYS. The parameter which are used in the study are shown in Table 1 and Fig. 1.

The investigation focuses on the change of vibration properties such as natural frequency of RC members which indicates the reduction in stiffness of reinforced concrete beam for various stages of monotonic load. The stages of pre crack are identified based on various stages of loading. The fundamental natural frequency of the damaged RC members was obtained by hammer impact test, in order to identify the relationship between damages level and changes of vibration characteristics due to flexure damage. The formation of cracks reduces the effective stiffness of the beam. At each of these stages the load deflection behaviour and natural frequencies were found from experiment.



(a) (b)

Figure 1. (a) Longitudinal Section (b) Beam Cross Section

4. EXPERIMENTAL STUDY

Static four point bending test was done on beams using loading frame and hydraulic jack. The beam was loaded in a traditional hydraulic loading system and the loading steps were performed by controlling displacement with a constant bending moment in the mid region. The specimens were supported by a pair of steel hinge-roller support with a span of 1400mm. The load was applied gradually through the hydraulic jack using loading frame. Linear variable differential transformers (LVDTs) were installed to measure the deflection at mid-point and they are connected to a data-logger and a computer.

The beam was loaded up to the formation of cracks or till the maximum deflection. The test were terminated till the ultimate load has attained. During loading process, the development of cracks were noted after every 10kN and patterns of the cracks were drawn on the beam specimen. As long as the beam behave as linear, the force F is increased with the constant rate. If there is any drop in force speed, this indicate the material softening (5). Due to softening of concrete micro-cracks develop over a small region of the beam. These micro cracks will form into a real crack whereas stresses increases.

The Young's modulus of Elasticity (E_c) can be computed as

$$\boldsymbol{E_c = 5000\sqrt{f_{ck}}} \tag{1}$$

$$f = \frac{E_c \varepsilon}{1+\varepsilon/\varepsilon o}, \varepsilon_o = 2f_{ck}/E_c\ , E_c = f/\varepsilon \tag{2}$$

where f = stress $at\ any\ strain\ \varepsilon, MPa,\ \varepsilon = strain\ at\ stress\ f,$ $\varepsilon_o = strain\ at\ the\ ultimate\ compressive\ strength\ f_{ck}$

The Modulus of rupture (f_{cr}) can be computed as

$$\boldsymbol{f_{cr} = 0.7\sqrt{f_{ck}}} \tag{3}$$

Table 1: Reinforced Concrete Beam Details

Beam Specimen	Concrete			Steel	
	$f_{ck,}$ Mpa	$f_{cr,}$ MPa	E_{c} , Mpa	$f_{y,}$ *MPa*	Percentage p_t, %
1	44.3	4.659	33279.12	415	0.362

Note: f_{ck} , is the cube compressive strength; f_y , is the Yield strength of the steel

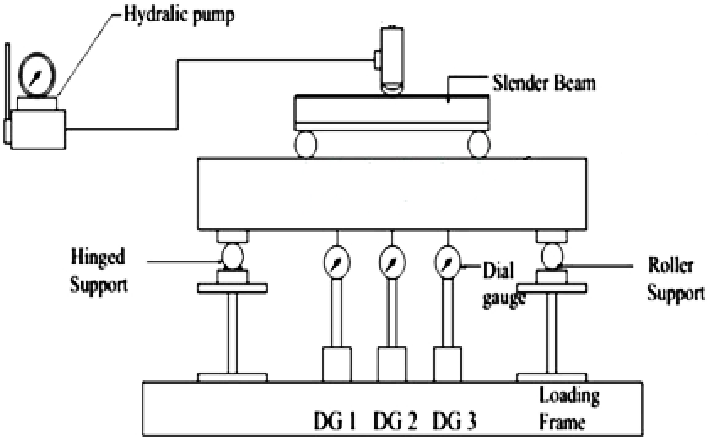


Figure 2. Test setup [5]

Figure 3. Testing of beam

4.1 Free vibration test

Free vibration test was performed initially before loading and after each 10kN loading interval. The free fall excitation was applied at the top of the RC beam element by using free fall of steel ball from particular height. The accelerometer was attached at the centre to measure free vibration in the vertical direction and to get fundamental natural frequency. The test was carried out by using the transfer function technique on RC beam, which was simply supported. The excitation from the input force was measured using DAQ and lab view software. The vibration data is acquired through a data logger. In vibration test, the sampling frequency and the resolution of the A/D convention were 5 kHz and 12 bit respectively.

The fundamental frequency of a simply supported beam can be expressed by

$$f \quad = \frac{1}{2\pi}\left(\frac{\pi}{l}\right)^2 \sqrt{EI}/\sqrt{\rho} \text{ (Hz)} \tag{4}$$

where E is the modulus of elasticity of concrete(Mpa); I of the moment of inertia of the cross section (m^4), ρ is the mass of the beam per unit length (kg/m^3) and L is the length of the span (m).

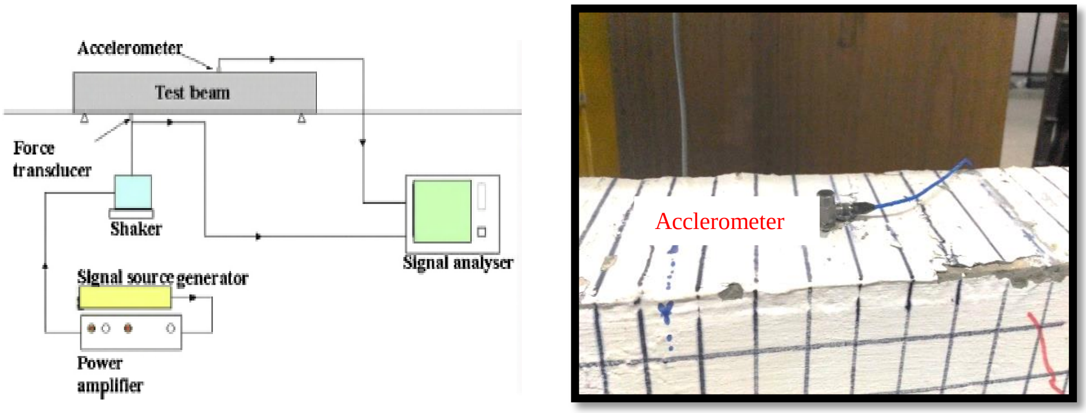
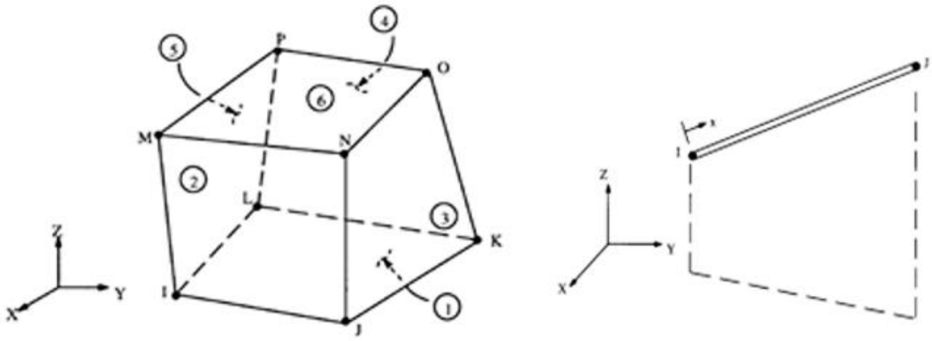


Figure 4. Accelerometer setup

5. NON LINEAR FINITE ELEMENT ANALYSIS

For nonlinear analysis, the ANSYS software was used to model and analyse the specimen. The modelling of specimen is done by using solid elements dimensionally same as experimental specimen. The material modelling for concrete used for this paper as per IS456:2000. In SOLID65 element, 8nodes with 3 DOFs at each node, capable of handling nonlinear behaviour, cracking in three orthogonal directions due tension and crushing in compression and plastic deformation and three perpendicular direction were included in reinforcement and it can be identified by the volume ratio of reinforcement steel. LINK 8 was used for model steel reinforcement. This element is a 3D spar element and it has two nodes with three degrees of freedom translations in the nodal x, y, and z directions, capable of handling plasticity, creep, swelling, stress stiffening and large deflection. The support and loading points were modeled as steel cushion to avoid stress concentration problems using eight-noded SOLID 45 element with three degree of freedom at each node, which handles plasticity and stress stiffening and large deflection. Parameters which are used for modelling are stated in table 1 and table 2. The analytical modelling as carried out in batch sequence using KEYPOINTS, LINES, VOLUME, VMESH and VSWEEP commands. The load deformation is computed from ANSYS.



(a)   (b)

Figure 5. (a) Solid 65 element (b) Link 8 element

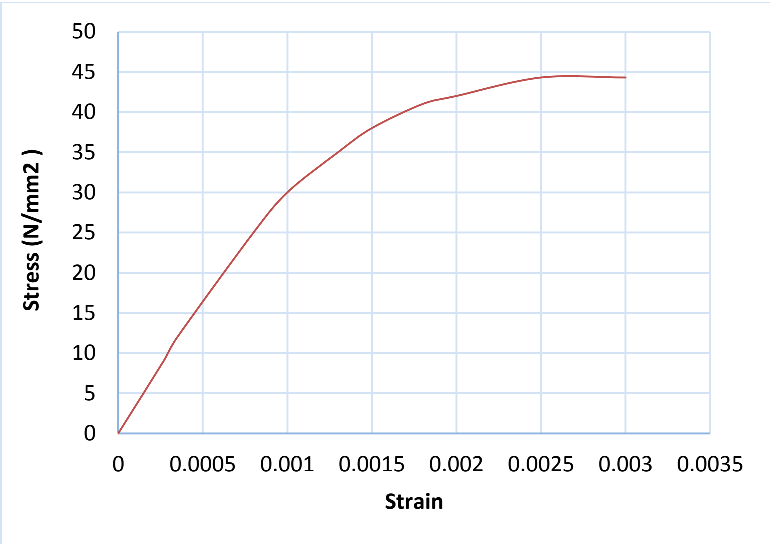


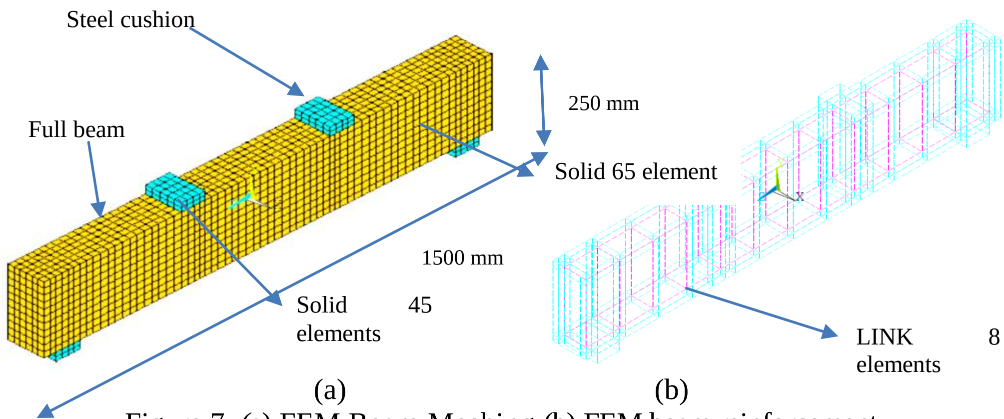
Figure 6. Stress – strain curve of concrete

Table 2: Materials properties for concrete and steel

Material Numbers	Element Type	Material Properties	
1	SOLID 65	Linear Isotropic	
		EX	33279.12 N/mm^2
		PRXY	0.2
		Concrete	
		Open shear transfer coefficient	0.3
		closed shear transfer coefficient	0.9

		Uniaxial Cracking Stress	4.427 Mpa
		Uniaxial Crushing Stress	43 Mpa
2	SOLID45	Linear Isotropic	
		EX	200000 Mpa
		PRXY	0.3
3	LINK 8	Linear Isotropic	
		EX	2000000 Mpa
		PRXY	0.3
		Bilinear Isotropic	
		Yield Stress	415 Mpa
		Tangent Modulus	20 Mpa

The support condition were given using displacement boundary conditions.The finite element analysis study included modelling of a concrete beam with properties and dimensions. For this research work , discrete method is used to model steel reinforcement in RC beam To create FEM model, command prompt line input or graphical user interface or ANSYS Parametric Design Language (APDL) is used. For this analysis, graphical user interface is used to create the model.



(a) (b)

Figure 7. *(*a) FEM Beam Meshing (b) FEM beam reinforcement

6. RESULT AND DISCUSSION

a) Displacement control

In static load, the external load is applied in the form displacement increment at mid-span and the result is obtained are presented in graph. The graph represent the prediction of load – displacement curve, which shows deflection of curve at each point of the load. Based on the experimental measurement the beam exhibits a ductile behaviour. With the load carrying capacity and the maximum deflection of the load point being approximately 80kN and 12 mm respectively; which shows the failure of the RC beam caused by yielding of the longitudinal reinforcement bars at the mid span, which leads to cracking of beam at ultimate load. Fig 3 shows how the RC beam deforms in the case of static loading. Where as in nonlinear analysis predicts a response of RC beam as similar to experimental beam which shows a the load carrying capacity is some what higher than experimental beam with same deflection (84kN and 12mm , respectively).

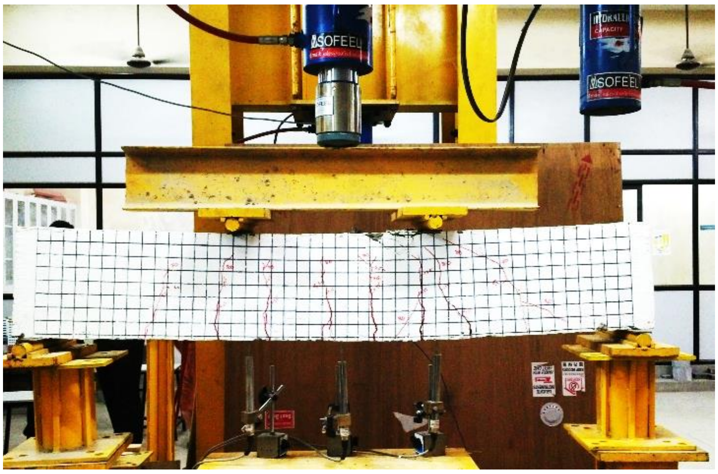


Figure 8. RC beam Deformation under Static Load

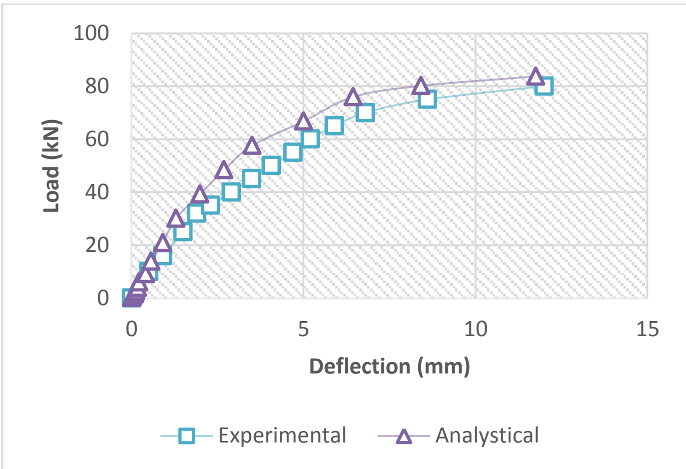


Figure 9. Graph of experimental and analytical analysis

b) Natural frequency

At each stage of static loading test, accelerometer reading were taken to detect the natural frequency in the beam specimen. Acceleration –time history were captured by using accelerometer equipment to detect frequency at each static loading with a sampling rate of 5kHz. Firstly, the natural frequency of undamaged beam sample was found as 209Hz and the reduction of natural frequency was quite limited until yielding of the main reinforcement. The frequencies significantly decreases just after yielding of reinforcement.

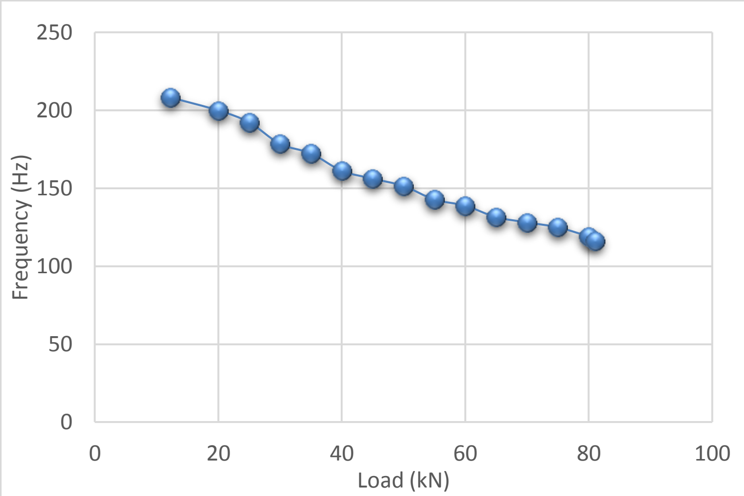


Figure 10. Graph of degradation of frequency as load increases

This changes in frequency leads to the stiffness degradation which eventually decrease flexural rigidity of the beam specimen. As per the IS 456:2000, the flexural rigidity of the beam is EI= 4941.058 kN-m^2. The static load test for conventional beam, gave the value of flexural rigidity from 5468.7 kN-m^2 to 1703.6 kN-m^2 for the load up to 81kN. The maximum moment under service load is M_{cr} = 6.066kN-m. The conventional load on the test beam cracks at 26.036 kN. The first crack was observed in test beam at 30 KN.

Table 3: Changes in flexural rigidity

Load (kN)	Frequency (Hz)	Flexural Rigidity EI(kNm^2)	Stiffness (kN/m)
12.2	208.33	5468.8	95409.12
20	200.00	5040.0	87931.86
25	192.30	4659.8	81291.44
30	178.57	4017.9	70097.62
35	172.41	3745.5	65344.82
40	161.29	3277.8	57187.5
45	156.25	3076.2	53669.35
50	151.51	2892.6	50462.51
55	142.85	2571.4	44858.71
60	138.88	2430.6	42399.98
65	131.57	2181.4	38053.97
70	128.20	2071.0	36129.53
75	125.00	1968.8	34348.38
80	119.04	1785.7	31151.01
81	116.27	1703.6	29718.14

7. CONCLUSION

It is important to adopt the effective stiffness in seismic analysis, particularly the equivalent lateral force method in which nonlinear properties of reinforced concrete beam are usually not implicitly accounted for the material constitution for the actual model. Thus, engineers should judge on the degradation of stiffness accordingly. This method is fairly good with the result obtained from static load test and this procedure is used to detect damage in RC beam by showing degradation of frequency which result in loss in the flexural stiffness.

The experimental and analytical study clearly establishes the stiffness degradation with the load going to non-linear stages. The method of predicting the flexural rigidity (EI_{eff}) uses the expression given proves to be effective.

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