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Evaluation of dynamic properties of extra light weight concrete sandwich beams reinforced with CFRP

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Abstract. Analytical and experimental investigation on dynamic properties of extra lightweight concrete sandwich beams reinforced with various lay ups of carbon reinforced epoxy polymer composites (CFRP) are discussed. The lightweight concrete used in the core of the sandwich beams was made up of extra lightweight aggregate, Lica. The density of concrete was half of that of the ordinary concrete and its compressive strength was about 100 Kg/cm^2. Two extra lightweight unreinforced (control) beams and six extra lightweight sandwich beams with various lay ups of CFRP were clamped in one end and tested under an impact load. The dimension of the beams without considering any reinforcement was 20 cm × 10 cm × 1.4 m. These were selected to ensure that the effect of shear during the bending test would be minimized. Three other beams, made up of ordinary concrete reinforced with steel bars, were tested in the same conditions. For measuring the damping capacity of sandwich beams three methods, Logarithmic Decrement Analysis (LDA), Hilbert Transform Analysis (HTA) and Moving Block Analysis (MBA) were applied. The first two methods are in time domain and the last one is in frequency domain. A comparison between the damping capacity of the beams obtained from all three methods, shows that the damping capacity of the extra lightweight concrete decreases by adding the composite reinforced layers to the upper and lower sides of the beams, and becomes most similar to the damping of the ordinary beams. Also the results show that the stiffness of the extra lightweight concrete beams increases by adding the composite reinforced layer to their both sides and become similar to the ordinary beams.

Keywords: extra lightweight concrete; CFRP; damping; sandwich beams; clamped beams.

1. Introduction

For better performance against the earthquake, a decrease in the weight of the structures is very important. For this purpose, many researches are focused on decreasing the concrete density to about 1700~1800 Kg/m^3.

In this study, our investigation was on an extra lightweight concrete with a density of about 1200 Kg/m^3. The most important advantage of using this concrete was that although it had very low density, it's compressive strength was acceptable.

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Nevertheless, due to the inherent relatively lower stiffness of extra lightweight concrete (compared to other commonly used building material like steel and ordinary reinforced concrete), their use in applications, where higher strength and stiffness are required, has been hindered. To overcome this shortfall, we should use some stiffer material to reinforce extra lightweight concrete beams.

FRP is a versatile class of material that can be engineered to enhance the stiffness and strength of extra lightweight concrete beams. Carbon fiber reinforced composite (CFRP) has similar compression and tensile properties and thus can be used in either compression or tension zones of extra lightweight concrete beams (Daniel and Ishai 1994, Mallic 1993). In parallel to the investigations conducted in the past on the use of metallic reinforcements, several studies have also reported the use of FRP materials as effective reinforcing agent. For instance Taheri *et al*. (2002) presented a summary of investigations that were aimed to assess the influence of various physical and mechanical parameters on the performance of reinforced concrete (RC) beams strengthened with FRP plates. Stoll *et al*. (2000) studied the design, fabrication and testing the failure of two full-scale high-strength concrete bridge beams with FRP products for pre-stressing and shear reinforcement. An analytical model is proposed by Maalej *et al*. (2003) to predict the load- displacement response of wall-like reinforced concrete columns strengthened with FRP raps. Yang *et al*. (2003) presented a fracture mechanics based finite element analysis of debonding failures in FRP plated RC beams. Yang *et al*. (2002) have done a research on interfacial stresses of a concrete column confined by FRP plate. Toutanji and Oritz (2001) studied and reported the experimental and analytical results of the influence of concrete surface treatment and the type of FRP sheets on the bonding strength of concrete-FRP sheet.

As well as these reports, some researches have been done on the damping characteristics of materials. Smith and Werely (1997) experimentally determined the damping levels that can be achieved by cocuring constrained viscoelastic damping layers in a composite beam. Analytical and experimental investigation were carried out by Naghipour *et al*. (2005) to evaluate the dynamic properties of a series of glued-laminated beams (glulam), reinforced with E-glass epoxy polymer composites (GRP)having various lay ups and thickness. Natural frequency of glulam beams reinforced with GFRP through nondestructive test has been investigated by Zou *et al*. (2003). Yim (2003) studied the damping behavior of a 0° laminated sandwich composite beam inserted with a viscoelastic layer. Theoretical prediction of the effect of fiber orientation and laminate geometry on the flexural and torsional damping and modulus of FRP has been made by Adams and Bacon (1973).

The standard test method for measuring the dynamic properties of material is given in ASTM E 756-98 and (SAE J1637 FEB93, 1993). Unreinforced and CFRP reinforced extra lightweight concrete beams were fabricated based on the standards established in an approved quality control manual, in accordance with ANSI/AITC A 190.1-1992.

This paper outlines three damping identification techniques both in time and frequency domain analysis. The methods under consideration in time domain are logarithmic decrement method (LDM) and Hilbert transform analysis (HTA) and in the frequency domain is Moving block analysis (MBA).

As well as damping, the lateral stiffness of beams was investigated. The result of stiffness and damping of these several beams and comparison between them are outlined in this paper.

2. Test setup and configuration

Tests were conducted to determine the first fundamental natural frequency of series of extra lightweight concrete beams reinforced with different configurations of Carbon/Epoxy fibers to use in the estimation of damping ratio of these beams. The investigation had four steps: finding a good mixture formulation for extra lightweight concrete, manufacturing of the beams, reinforcing the beams with carbon fiber reinforced polymer, and testing of the beams.

First of all, the work was concentrated on finding a good mixture formulation for extra lightweight concrete. A great fraction of aggregates in this extra lightweight concrete was a special kind of extra lightweight aggregate named Lica. Lica is an artificial aggregate that is made up of burnt clay. Its density is about 750 Kg/m^3. The maximum size of aggregate used in extra lightweight concrete was 9.54 mm.

Eventually we made a concrete which its density was about 1200 Kg/m^3 and it's compressive strength was about 100 Kg/m^2. All of the extra lightweight concrete beams were made by this kind of concrete in Mazandaran University's laboratory.

The overall dimensions of the beams were 140 cm × 20 cm × 10 cm. These dimensions were selected to ensure that the effect of shear during the bending test would be minimized. Carbon fiber reinforced polymer sheets were the reinforcements that sandwiched the extra lightweight concrete. The angle of fiber orientation in CFRP sheets were [0^o] and three lay ups were used to reinforce the extra lightweight concrete beams. (See Table I). The CFRP plates were adhered to the top and bottom surfaces of the aforementioned series, while [0°_2] laminates were used to reinforce the beams of series A, [0^o_4] laminates used to reinforce the beams of series B and the beams of series C were reinforced by [0^o_6]. As well as these series, the beams of series L, which are extra lightweight concrete beams without any reinforcement and the beams of series O, which are the beams made up of ordinary concrete beams with steel bar reinforcement were taken into account. In fact, CFRP reinforced beams are sandwich beams that extra lightweight concrete was used as a core material and CFRP sheets as two face plates. Extra lightweight concrete beams without and with reinforcement are shown respectively in Figs. 1 and 2. All of the beams were clamped in the length of 20cm of their end. The fixed end of the beam is shown in Fig. 3, and the test setup is given in Fig. 4.

3. Stiffness of the beams

An initial displacement on the free end of the beams was applied in order to make a free vibration in them. The free end of the beam was pulled by a wire connected to this point and suddenly the wire was cut and the beam started to vibrate. The load applied to pull the end of the beam was about 100 Kg.

Table 1 Dimensions of beams used in experiments

Type \ Beam	Beam No.	Weight (Kg)	Beam's Dimensions			Density Kg/m^3
			Length (cm)	Width (cm)	Height (cm)	
A (with 2 layer reinforcement)	1	33.650	139.5	20.1	9.9	1212.2
	2	33.540	140.2	20	9.85	1214.4
B (with 4 layer reinforcement)	1	33.200	141.1	20.1	10	1170.6
	2	33.350	139.6	19.9	10.1	1188.6
C (with 6 layer reinforcement)	1	33.520	140.4	19.9	10	1199.7
	2	34.250	140.2	20	10.2	1197.5
L (without any reinforcement)	1	65.950	139.9	20	10.1	2333.7
	2	67.560	141.3	20.3	10.1	2332
O (ordinary beam with steel rebar)	1	33.120	140.7	20.2	10.1	1153.8
	2	33.080	140.5	20.1	10.1	1159.8

Fig. 1 Extra lightweight concrete beam without reinforcement

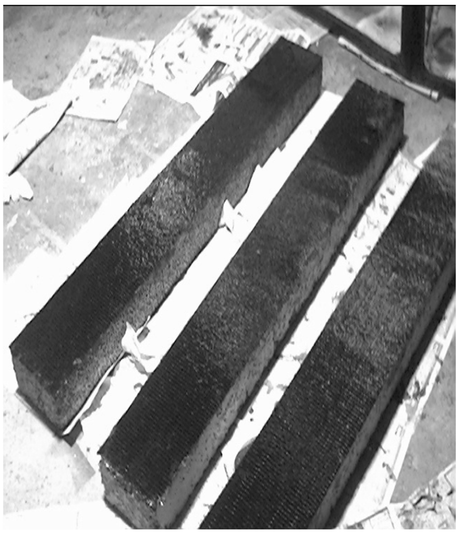

Fig. 2 CFRP reinforced extra lightweight concrete beam

The load and displacement of the beam was recorded on the computer. Figs. 6 and 7 show the load and beam's displacement in one of the tests. As shown in the figures, at first, both load and displacement are linear versus time that this part of them has been used for measuring the lateral stiffness of the beams.

By plotting the linear part of the load versus the linear part of the displacement, the stiffness of the beam can be extracted. Stiffness is the slope of the best linear fitted equation of this diagram. It should be noted that the point (0,0) must be on the fitted line and the other point can be found by the least square principle. Fig. 8 shows the diagram and fitted line for one of the beams.

Details of all measurements which were used for stiffness of five types of beams in several tests are

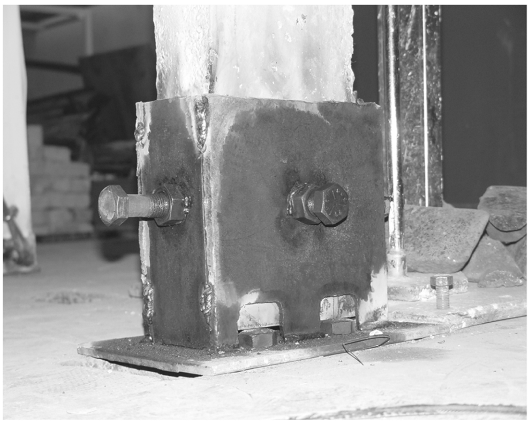

Fig. 3 Fixed end of the beam

Fig. 4 Test setup

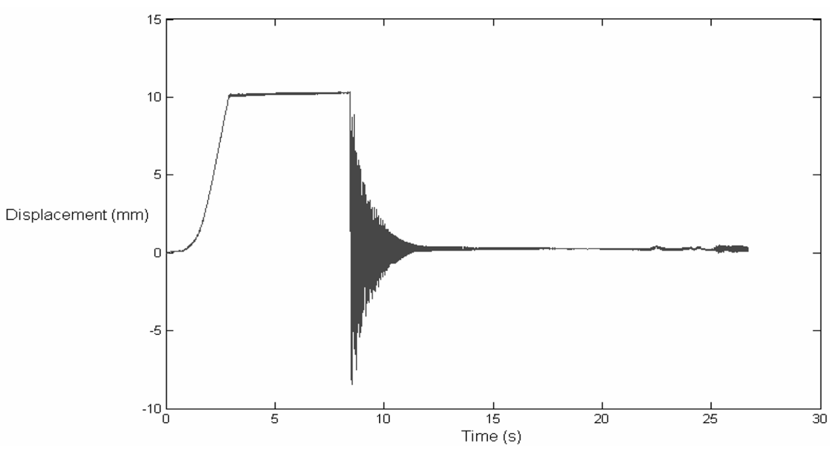

Fig. 5 Displacement of the beam vs. time

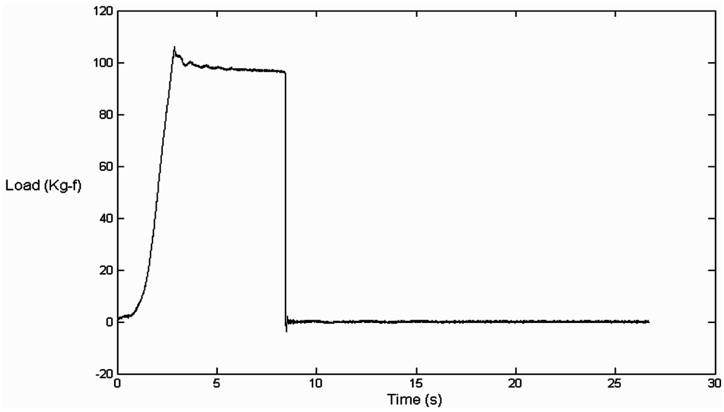

Fig. 6 Applied load vs. time

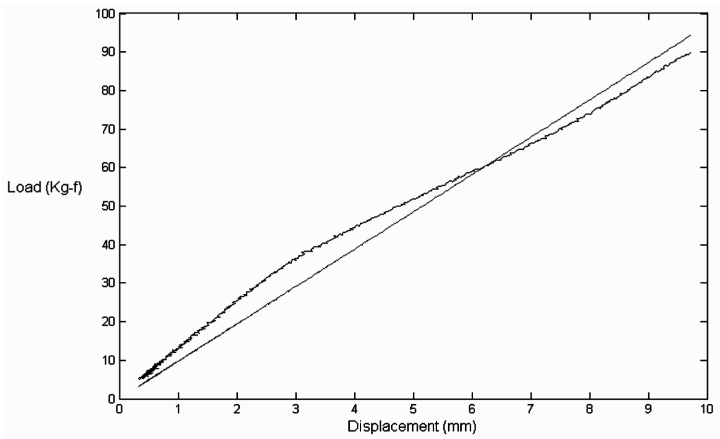

Fig. 7 Diagram of load versus displacement and fitted line

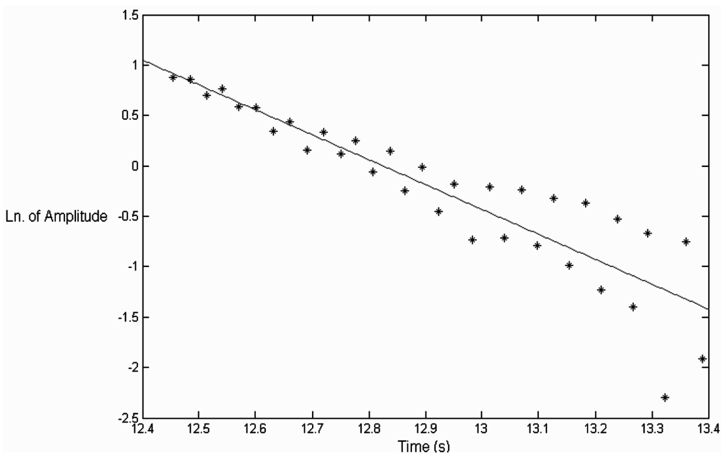

Fig. 8 Natural logarithm of amplitude in each half cycle versus time

Table 2 Stiffness of the beams

Beam / Type	Beam No.	(kg-f/mm) Measuring the Stiffness of System				
		Test 1	Test 2	Test 3	*K* (mean)	*K* (mean)
A (with 2 layer reinforcement)	1	9.691	10.6143	11.0903	10.4652	10.386
	2	10.3191	10.5783	10.0232	10.3069	
B (with 4 layer reinforcement)	1	11.4592	14.1532	10.2187	11.9437	12.9477
	2	14.7697	14.8875	12.1981	13.9518	
C (with 6 layer reinforcement)	1	14.7901	11.9729	13.1671	13.3100	14.4027
	2	15.1426	15.0945	16.2494	15.4955	
L (without any reinforcement)	1	3.6439	2.7181	3.2546	3.2055	3.0842
	2	2.1756	3.7569	2.9562	2.9629	
O (ordinary beam with steel rebar)	1	12.2922	13.9420	13.2545	13.1629	13.6683
	2	15.806	13.7474	12.9678	14.1737	

given in Table 2. It is shown that reinforcement of the beams with CFRP sheets and steel bars increases the stiffness of them.

4. Estimation of damping ratio using different method of analysis

Different methods of analysis have been considered in this study. In time domain analysis two different methods, LDA and HTA have been used for evaluation of damping ratio, and in frequency domain, MBA method were used and are discussed later.

4.1 Determination of damping ratio by logarithmic decrement analysis (LDA):

The logarithmic decrement technique is one of the most common methods for damping estimation in time domain. The logarithm of the ratio of the amplitude of two oscillation, n cycles apart from each other on the decaying transient of a single degree of freedom system, is logarithmic decrement δ, is given as:

$$\delta = Ln\left(\frac{y_m}{y_{m+n}}\right) \tag{1}$$

In which m^{th} peak amplitude and the amplitude of n cycles apart from that are measured from the equation of transient signal and the damping ratio is given as:

$$\xi \cong \delta / 2\pi n \tag{2}$$

So the damping ratio can be determined from the slope of the best fitted line to the natural logarithm of each peak magnitude. The slope is equal to $-\xi\omega_n$ (Smith and Werely 1997), (See Fig. 8 and Table 3).

The table shows that all kinds of reinforcements decreases the damping ratio of beams from 0.07 to about 0.02.

4.2 Determination of damping ratio by Hilbert Transform Analysis (HTA):

Hilbert transforms are linear operators which can be defined for a $x(t)$ time series by a convolution integral as :

Table 3 Determination of damping ratio using Logarithmic Decrement Analysis (LDA)

Type \ Beam	Beam No.	Damping Capacity of System				
		Test 1	Test 2	Test 3	ζ (mean)	ζ (mean)
A (with 2 layer reinforcement)	1	0.0204	0.0208	0.0204	0.0205	0.0193
	2	0.0164	0.0161	0.0222	0.0182	
B (with 4 layer reinforcement)	1	0.0220	0.0224	0.0195	0.0213	0.0183
	2	0.0150	0.0153	0.0159	0.0154	
C (with 6 layer reinforcement)	1	0.0124	0.0182	0.0126	0.0144	0.0139
	2	0.0140	0.0138	0.0126	0.0135	
L (without any reinforcement)	1	0.0752	0.0896	0.0693	0.0780	0.0732
	2	0.0523	0.0726	0.0804	0.0684	
O (ordinary beam with steel rebar)	1	0.0135	0.0208	0.0186	0.0176	0.0158
	2	0.0127	0.0149	0.0148	0.0141	

$$H[y(t)] = \int_{-\infty}^{+\infty} \frac{y(u)}{y(t-u)} du \tag{3}$$

However a way to define the Hilbert transform is as 90 deg phase shift system. Thus $H[y(t)]$ is simply $y(t)$ shifted by 90 deg. Assuming viscous damping, the decaying transient of a single degree of freedom system is given by:

$$y(t) = e^{-\xi\omega_n t}\cos(\omega_d t + \varphi) \tag{4}$$

The Hilbert transform is the same signal, but phase shifted 90 degree, as:

$$H[y(t)] = e^{-\xi\omega_n t}\sin(\omega_d t + \varphi) \tag{5}$$

Also an analytic signal [$z(t) = x(t) + iy(t) = Ae^{i\theta(t)}$] has a real part which is the original data and an imaginary part that contains Hilbert transform. The amplitude is the absolute value of analytic signal A(t), which is called envelope signal of $x(t)$, (Fig. 9), can be defined as:

$$A(t) = \sqrt{x^2(t) + y^2(t)} \tag{6}$$

Now from this background the damping analysis consists of calculating the envelope signal for the transient data, using Hilbert transformation. As we know for the transient response of a viscously damped system, the envelope signal, $A(t)$, can be given as:

$$A(t) = e^{-\xi\omega_n t} \tag{7}$$

So a line can be fitted to the logarithm of the envelope signal and the slope of this line is $-\xi\omega_n$, which gives the damping ratio (Smith and Werely 1997), (See Fig. 10).

The results of damping ratio determined from this method which are similar to LDA method are given in Table 4.

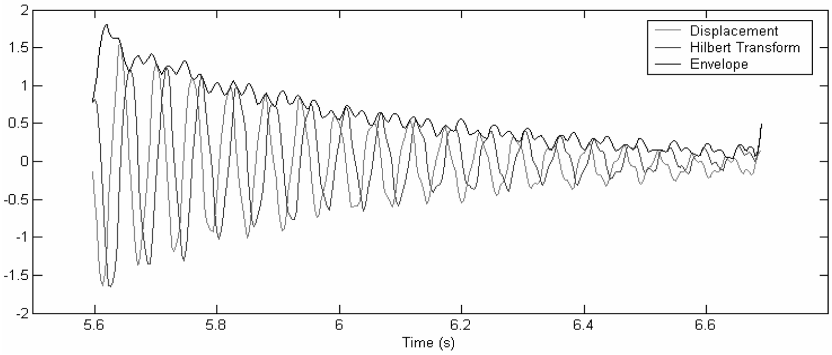

Fig. 9 Displacement, Hilbert transform of displacement and their envelope

4.3 Determination of damping ratio by Moving Block Analysis (MBA):

Moving block analysis is commonly used in the rotorcraft industry to identify damping of rotor modes such as blade flap, lag, and torsion modes. The moving block analysis is based on calculation of discrete approximation FFT of blocks over the transient response data. For a damped transient response it can be written as:

$$F(\omega, t_0) = \int_{t_0}^{T+t_0} Ae^{-\xi\omega_n t}\sin(\omega_d t + \varphi)e^{-i\omega t}dt \quad (8)$$

Where, $\omega_d = \sqrt{1-\zeta^2}\,\omega_n$ the damped natural frequency, t_0 the initial time of the FFT, and $T + t_0$ the final time of the FFT. Here T is defined as the length of the block. The natural logarithm of the magnitude of the FFT at the frequency of interest is given approximately by:

$$Ln|F(\omega_n, t_0)| = -\xi\omega_n t_0 + Ln\left(\frac{A}{2\omega_0}\right) + 0.5Ln\, f(\zeta, t_0) \quad (9)$$

The graph of the natural log of the magnitude of the FFT, $Ln|F(\omega_n, t_0)|$ versus time, t_0, is the superposition of a straight line with slope $-\xi\omega_n$ and a component that oscillate about the line with frequency $2\omega_n$. The damping ratio is readily determined from the slope of the line (Smith and Werely 1997), (See Fig. 11 and Table 4).

From the table it is seen that different methods, even MBA method, are giving similar results for dynamic parameters of reinforced sandwich beams.

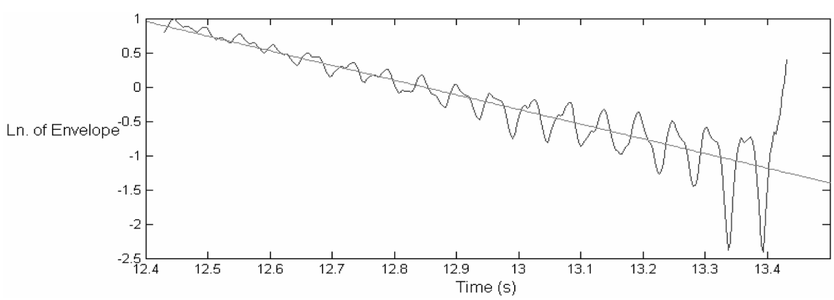

Fig. 10 Natural logarithm of the envelope and fitted line

Table 4 Determination of damping ratio using Hilbert Transform Analysis (HTA)

Type \ Beam	Beam No.	Damping Capacity of System				
		Test 1	Test 2	Test 3	ζ (mean)	ζ (mean)
A (with 2 layer reinforcement)	1	0.0278	0.0231	0.0206	0.0238	0.0197
	2	0.0155	0.0150	0.0165	0.0156	
B (with 4 layer reinforcement)	1	0.0222	0.0197	0.0199	0.0206	0.0192
	2	0.0154	0.0172	0.0212	0.0179	
C (with 6 layer reinforcement)	1	0.0147	0.0173	0.0135	0.0152	0.0151
	2	0.0150	0.0162	0.0137	0.0150	
L (without any reinforcement)	1	0.0746	0.0635	0.0583	0.0655	0.0693
	2	0.0638	0.0759	0.0795	0.0731	
O (ordinary beam with steel rebar)	1	0.0128	0.0164	0.0159	0.0150	0.0153
	2	0.0158	0.0162	0.0151	0.0157	

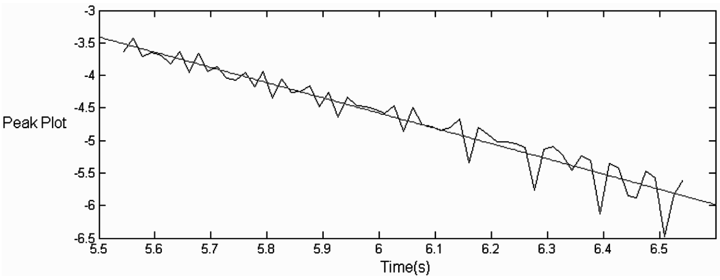

Fig. 11 Peak plot versus time and fitted line

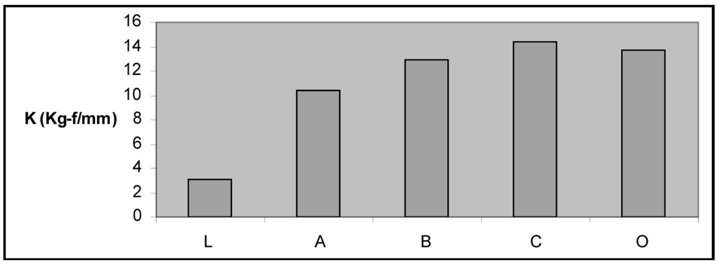

Fig. 12 A comparison between the stiffness of the beams

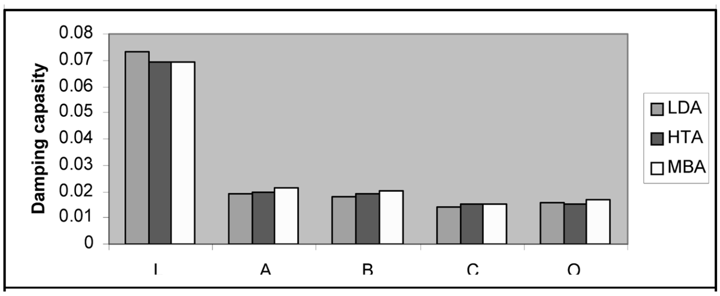

Fig. 13 Comparison between the damping capacity of different beams

Table 5 Determination of damping ratio using Moving Block Analysis (MBA)

Type \ Beam	Beam No.	Damping Capacity of System				
		Test 1	Test 2	Test 3	ζ (mean)	ζ (mean)
A (with 2 layer reinforcement)	1	0.0231	0.0267	0.0234	0.0244	0.0215
	2	0.0189	0.0193	0.0180	0.0187	
B (with 4 layer reinforcement)	1	0.0201	0.0228	0.0207	0.0212	0.0204
	2	0.0161	0.0196	0.0232	0.0196	
C (with 6 layer reinforcement)	1	0.0151	0.0171	0.0139	0.0154	0.0153
	2	0.0156	0.0162	0.0139	0.0152	
L (without any reinforcement)	1	0.0634	0.0635	0.0583	0.0655	0.0693
	2	0.0638	0.0759	0.0795	0.0731	
O (ordinary beam with steel rebar)	1	0.0133	0.0187	0.0199	0.0173	0.0169
	2	0.0159	0.0165	0.0170	0.0165	

5. Conclusions

In this study we experimentally evaluated the dynamic properties of CFRP reinforced extra lightweight concrete beams. Fig. 12 shows the beams' stiffness in comparison with each other. It can be understood from the figure that extra lightweight concrete beams' stiffness increase by adding the composite reinforced layer on their both sides and their stiffness became more similar to the ordinary beams.

The damping capacity of the beams has shown in Fig. 13. Approximately, all of the three methods came up to the same result in measuring the damping capacity. A comparison between the damping capacity of beams obtained from all the methods of analysis, shows that the damping capacity of the extra lightweight concrete decreases by adding the composite reinforced layers on their both sides and it becomes most similar to the damping of the ordinary beams.

When extra lightweight concrete beams were reinforced with CFRP, in both stiffness and damping capacity, they showed a behavior like the ordinary beams reinforced with steel bars.

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