

Damage Investigation on RC Beam Specimens Subjected to Static and Fatigue Loading Utilizing Laser Doppler Vibrometer (LDV)

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1. Introduction

Damage investigation on structures after a certain period of service life has become an indispensable need to secure safety for the people who use them. As has been described by the Author [3], the concern about degree of embedded damages in structures has been made even more complicated by dimension of the structures and existence of partial deterioration level across each body. Both hindering problems lead to a need to have a means of nondestructive investigation that will behave as an early-warning system and it tops the hierarchy of damage investigation.

Regular methods of nondestructive investigation, such as those using ultrasonic, impact echo, radar, thermograph, etc, can only capture partial information of an overall structure since the data acquisition is performed part-by-part so that no possibility to take all damage-containing "pictures" of the overall structure. Moreover, the application of them is usually initiated by preliminary detected bare-eyes surface deterioration, such as spalling of concrete, crack existence, etc, that completely gives no function of prevention or security.

As a result, the Author [3] has proposed the use of Laser Doppler Vibrometer (*LDV*) that has the power to perform the task. In application of it, a framework of damage investigation consisting methods of data acquisition and analysis has been developed, and it is labeled as "System Identification Algorithm" (*SIA*) (please refer to Figure 1).

Considering reinforced concrete (RC) structures, deteriorations of them are mainly induced by static and fatigue loading. However, these ordinary damage inducements are made compli-

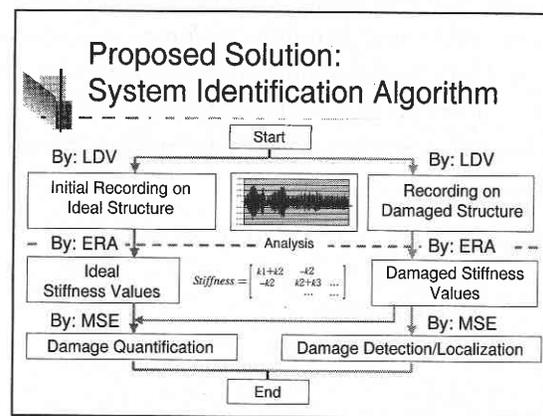


Fig. 1 System Identification Algorithm (SIA) for performing overall damage investigation.

cated by non-linear and elasto-plastic mechanical behavior of concrete. Due to these, experiments about damage investigation on 2 RC beam specimens had been done to investigate the extent of SIA's applicability to detect, localize, and quantify damages in RC structures.

2. Summary of Theories

In summary, damage investigation using *LDV*, within the SIA framework, is done in 3 stages: the first is data acquisition capturing velocity of ambient vibration of a structure; the second is structure's stiffness identification taking the power of Eigensystem Realization Algorithm (*ERA*); the third is damage detection/localization and quantification taking the advantage of Modal Strain Energy (*MSE*) method [3].

In giving judgment about level of damage, the damage detection and quantification cannot be separated; the former will identify location of damaged elements especially the one (s) severely damaged. However, we still have no information about degree of

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damage of it that is used further to make decision whether to do repair work or not. The damage quantification will then functions as a damage meter which quantifies level of damage of the mostly damaged element. Having this information, and making a cross-reference with the value of Relative Modal Strain Energy Change Ratio (MSECR) of each element, the magnitudes of damages of all elements can be all identified and put into a list sorted according to degree of severity. Finally, repair work should be done according to that priority list.

2.1 Damage Detection/Localization

Damage detection is done based on Modal Strain Energy (MSE) approach having the principle that deteriorated structure has change in its mode shapes. Strain energy is described as the potential energy stored in a body by virtue of an elastic deformation, equal to the work that must be done to produce both normal and shear strains. Localization of damaged elements is done based on relative $MSECR_j$ values calculated following the formulas as written below:

$$MSE_{ij} = \Phi_i^T K_j \Phi_i; \quad MSE_{ij}^d = \Phi_i^{dT} K_j \Phi_i^j \dots \dots \dots (1)$$

$$MSECR_{ij} = \frac{|MSE_{ij}^d - MSE_{ij}|}{MSE_{ij}} \dots \dots \dots (2)$$

$$MSECR_j = \frac{1}{m} \sum_{i=1}^{Dof} \frac{MSECR_{ij}}{MSECR_{i, \max}} \dots \dots \dots (3)$$

where ϕ denotes eigenvector, K represents element 's stiffness, and d is for damage.

2.2 Damage Quantification

In order to quantify the damage, 2 essential values need to be calculated beforehand, which are Modal Strain Energy Change ($MSEC_{ij}$) that represents actual strength of damaged structure and β_{st} that represents initial strength of the structure. $MSEC_{ij}$ and β_{st} can be interconnected with a factor α that measures reduction of strength from the initial original to the current actual, that is the degree of damage itself.

$$MSEC_{ij} = \beta_{st} \alpha \dots \dots \dots (4)$$

where:

$$\beta_{st} = - \frac{2}{Dof} \sum_{r=1}^{Dof} \Phi_{is}^T K_s \frac{\Phi_{is}^T K_i \Phi_{it}}{\lambda_r - \lambda_i} \Phi_{rs} \quad (r \neq i) \dots \dots \dots (5)$$

$$MSEC_{ij} = \Phi_i^{dT} K_j \Phi_i^d - \Phi_i^T K_j \Phi_i \dots \dots \dots (6)$$

In assessing the damage using Eq. (4), a certain mode shape i should be pre-chosen and values of $MSEC_{ij}$ and β_{st} are calculated

according to it. However, the Author [4] has performed a simulation that generated a conclusion about a better use of lower mode shape in evaluating Eq. (4) to Eq. (6). Therefore, in the analysis part, mode shape 1 will be used to measure damage values α .

3. Experimental Procedures

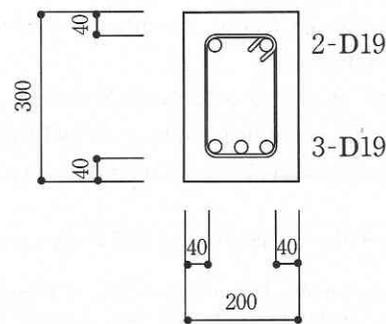
Two beam specimens were designed to have similar dimensional and strength properties, as outlined in Table 1. Each beam has 340 cm length and the load was applied at mid-span as 2 concentrated-equal magnitude point loads, separated 90 cm apart. The beams were designed to have initial crack at 2-ton load level and final failure at 14.5-ton load level in the form of compressive failure.

Each beam was modeled into a MDOF system consisting 11 spring-interconnected lumped masses. Therefore there were 12 springs whose characteristic values referred as "stiffness". The lumped masses were named with capital letters A to M and the springs were labeled with number 1 to 12, as depicted in Figure 2. In order to obtain actual progressively-reduced stiffness values of each beam, 5 transducers T_n were installed below point C, E, G, I, and K. The recorded deflection rate during loading was used to calculate concrete integrity EI (Young modulus E_c multiplied by un-cracked moment of inertia I) so that exact stiffness values of the object beam were identified.

In the experiment, Beam 1 was subjected to static loading and Beam 2 to fatigue loading. Each loading was applied following the schemes depicted in Fig. 3.

Table 1 Dimensional and Strength Properties

Beam	Dimension		Concrete Property		Steel Property	
	h (cm)	b (cm)	fc' (MPa)	Ec (MPa)	fy (MPa)	Young Mod. (MPa)
Beam 1	30	20	22.2	23500	400	170000
Beam 2	30	20	22.2	23500	400	170000



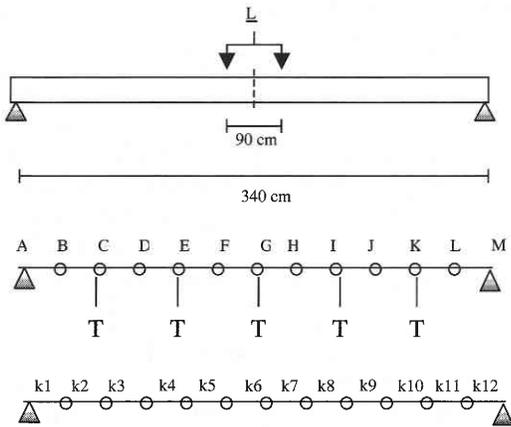


Fig. 2 Beam Discretization

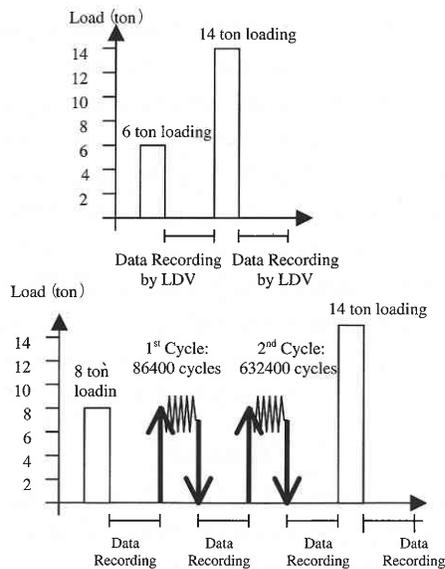


Fig. 3 Outline of Experiment

4. Analysis and Discussion

The analytical part was first done by extracting stiffness values of the beams using *ERA* [4]. Following that, damage localization using *MSE* method was performed whose results are as depicted in Fig. 5 and Fig. 6 for Beam 1 (static) and Beam 2 (fatigue) respectively. In every graph, the circles denote misleading peaks and the arch-line represents expected distribution of damage across beam length.

Damage on RC beam due to static loading is characterized by existence of damage concentration on several elements and arch-shape distribution of damage. From results of Beam 1 (Fig. 5) we can see ability of *SIA* (and *LDV*) to capture information about damage concentration that mainly took place in the middle part of

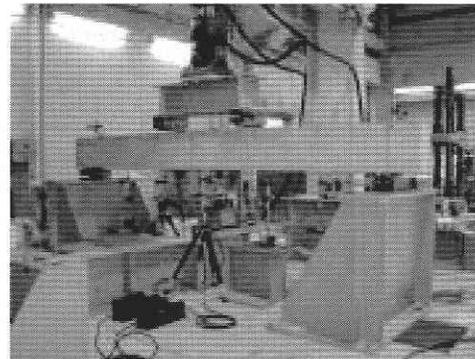


Fig. 4 The Overall Experimental Setting-Up

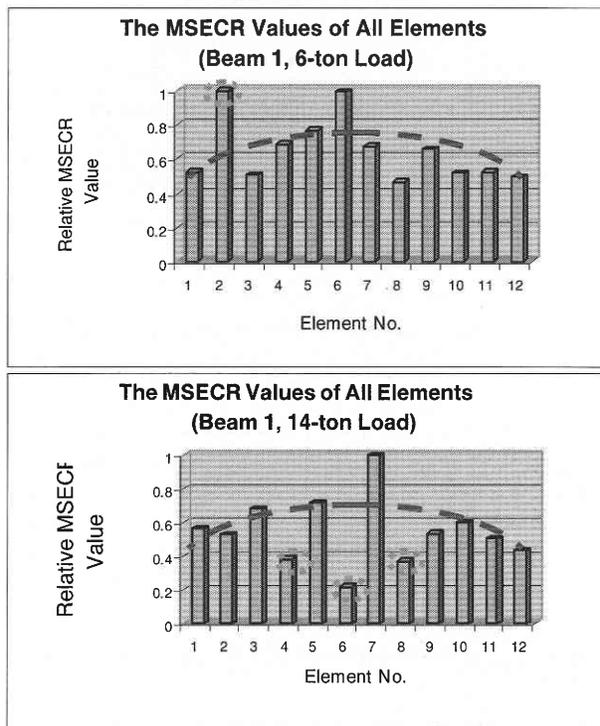


Fig. 5 Damage Localization for Beam 1.

Beam 1. Damage distribution across length of Beam 1 was found following an arch-shape, as had been expected. However, result of 14-ton load was ruined with few misleading peaks due to both existence of strength recovery, as the result of load removal before data recording, and noise that ruined recorded data.

As the phenomenon of strength recovery (due to induced compressive stress after load removal as a result of contacts between 2-adjacent crack surfaces that retain full closing of crack opening) becomes prominent after number of cracks increases, result of 14-ton load is the one prominently showing such mechanism. In addition, ambient vibration recording is always corrupted with

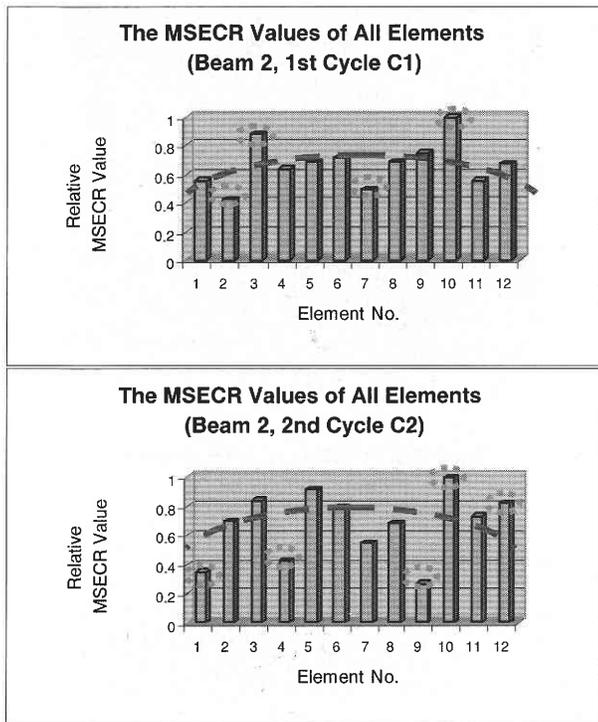


Fig. 6 Damage Localization for Beam 2

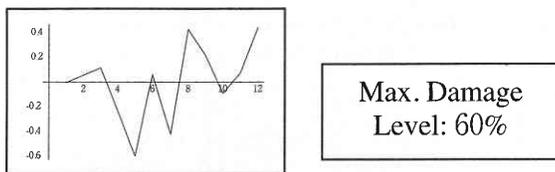


Fig. 7 Damage Quantification for Beam 1

noise that impairs information about structure's vibration properties.

Slightly different with static loading case, damage due to fatigue loading is characterized dominantly by an arch-shape damage distribution. Results of damage detection for Beam 2 (Fig. 6) confirm previous findings about ability of SIA and LDV to capture the configuration. Again, due to existence of strength recovery and noise-corrupted data, result of C2 cycle is ruined with several misleading peaks.

Considering ability to quantify damage, SIA could identify level of maximum damage at 60% in Beam 1. Moreover, it could capture 10% increase of damage level due to additional applied fatigue loading from 86400 cycle (C1) to 718800 cycle (C2).

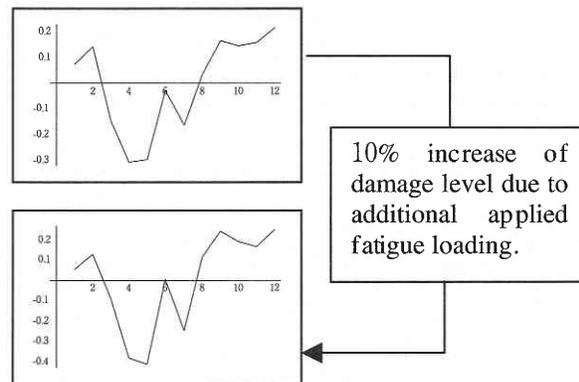


Fig. 8 Damage Quantification from C1 to C2

5. Conclusion

A framework to perform overall damage investigation using LDV, named as SIA, has been proposed. The ability of it to detect and quantify damage in RC structures has been explored whose results confirm previously foreseen potentials. Few weak points of SIA have been identified and they are caused by, first, noise-corrupted data and secondly by application of linear ERA and MSE method that obviously succeeds only until a certain degree when we deal with RC structure whose mechanical behavior is non-linear. Further improvement work will deal on noise elimination problem and formulation of non-linear ERA and MSE method.

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