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A NON-BASELINE DAMAGE IDENTIFICATION METHOD BASED ON THE STATIC STRAIN RESPONSE

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ABSTRACT
A non-base line damage identification method based on the distributed static strain response measurement is presented in this paper. A new approach for damage localization and quantification has been derived and verified with the numerical simulation results. The structural condition at the intact state is not required for the identification or localization of the damage. Sensor configuration to be installed on the structure along with the measured response can be used to identify and localize presence of any damage. To examine and illustrate the damage identification method, a numerical simulation study on a beam type structure was performed.

Keywords: Non-baseline damage identification, Distributed strain sensing, Macro strain.

1. INTRODUCTION
The diagnostic identification of damages of civil and mechanical engineering structures is of increasing interest for the past several decades. To this purpose, nondestructive testing is of great interest under several respects, because it can provide a direct assessment of integrity of structures during service or can be employed to assess the residual resistance of a structure after the occurrence of a strong seismic event.

Several damage identification methods based on measurement of the static and dynamic response of the structure have been proposed in the last decades. A detail review on the vibration based damage identification methods can be found in [1,2]. In cases of simple structural system, such as straight beams, subject to damage, static tests are easily executable and provide additional information to dynamic identification without any introduction of uncertainties due to inertia distribution and damping ratios. The static test can also be valuable as prerequisite to the modal and transient analysis [3]. However, damage identification based on the measurement of static response has been paid less attention compared to the dynamic response. Most of these damage identification techniques used the static displacement [3,4,5,6] and the health status of the intact structure should be known. Of these damage identification methods, a system identification methods using the static deflection and vibration modes of the structure has been developed by Hajela and Soerio [4] in which response of the original structure was obtained from the analytical model of the structure. Sanayei and Onidede [6] developed a method to identify the properties of structural elements by applying static forces to a set of degrees of freedom (DOF) and measuring the displacements at another set of DOF. Choi et al. developed an elastic damage load theorem to identify damage in beam type structures based on the static displacement response of the structure. However, measurement of the displacement at the site is a troublesome task and the health status of the intact structure from the numerical models involved a lot of redundancies.

Moreover, most traditional measurements such as accelerations, velocities and displacements are essentially “point” measurements at translational DOF. Such translational responses are global quantities of structures which are considered being insensitive and having no clear relationship to a specific local damage even near the transducers. Moreover, for the case of multi-damages at different locations or different kinds of damages, the situation will be extremely intricate. The mutual influence of structural damages on the measurements makes it difficult to perform effective structural parametric and damage identification.

Strain may be the most sensitive response to local damage. However, the influence of damage on strain measurement cannot be reflected effectively unless the area where strain sensor is fixed exactly covers the damaged region, which puts the corresponding sensors and their placements into a quite tough situation due to the fact that structural damage is an arbitrary and unforeseen phenomenon. Actually, traditional foil strain gauges are far from taking the task to monitor a structure not only owing to the problem of stability, durability and long-term reliability but also due to the difficulty for large area of distributed placements.

In recent days fiber optic sensing technology has opened the door of distributed sensing with a gage length upto several meters [7]. Among the fiber optic sensors, fiber bragg grating (FBG) based strain sensor are most suitable with its special features of high accuracy level, stable sensing capacity and so on. Li and Wu [7] developed a long-gage fiber optic sensor which can be used to measure the structural response distributedly by placing the sensors in series.

This paper focuses on detecting and assessing damage in beam type structures from measured static strain response. With the proposed method damage detection and/or quantification can be done with no requirement for an analytical model and/or health condition of the intact or undamaged structure. Damage identification can be performed by directly utilizing the measurements from various sensors. The proposed non-baseline damage identification method has been verified by a simulation case study.

2. NON-BASELINE DAMAGE DETECTION TECHNIQUE

The flexural stress of a beam at any section *x*, as shown in Fig.1, can be calculated as

$$\sigma_x = \frac{M_x y}{I} \quad (1)$$

and the corresponding strain is

$$\varepsilon_x = \frac{M_x y}{EI} \quad (2)$$

where M_x is the bending moment at any section *x*, σ_x and ε_x are the corresponding flexural stress and strain at the same section respectively. *y* is the distance of the fiber from the neutral axis where the stress or strain to be calculated, *E* and *I* have their usual meaning.

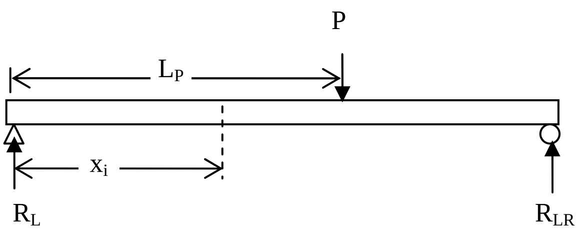


Fig.1. Basic concept of the proposed method

For an intact beam the stress or strain at any section solely depends on the magnitude of the moment. For a given configuration and a set of loads, the moment at any section can be expressed as a function of x, the measurement location. Therefore, the ratio of the strain between two measurement locations for a given loading configuration is independent of the magnitude of the load and will be a constant. This ratio will remain constant for the same load configuration with varying amplitude of the load. However, the ratio of strain between two measurement locations will be changed if there exists damage in any one of the sections. The change in the strain ratio will depend on the local reduction of the flexural rigidity of the beam. Thus this ratio can help to detect and quantify the damage.

2.1 Damage Localization

Consider a simple supported beam with a concentrated applied load at a distance L_P from the left support. The equation of the moment at any section, x_i ($x_i \le L_p$), from the left support is

$$M_x = R_L x_i \quad (3)$$

where R_L is the left support reaction.

Using Eq.(2) and Eq. (3) the strain at any section x_i , is

$$\varepsilon_i = \frac{R_L x_i y}{EI} \quad (4)$$

Similarly, the strain at any reference location, x_R, can be written as

$$\varepsilon_R = \frac{R_L x_R y}{EI} \quad (5)$$

Using Eq. (4) and Eq. (5), ratio of the strain between these two locations can be found as

$$\frac{\varepsilon_i}{\varepsilon_R} = \frac{x_i}{x_R} \quad (6)$$

The strain ratio, which can be defined as the ratio of the strain of any *i*th element to that of a reference sensor is

$$\gamma_i = \frac{\varepsilon_i}{\varepsilon_R} \quad (7)$$

From Eq. (6) it is clear that for a given configuration of load the ratio of the strain between two measurement locations is equal to the ratio of the distances measured from the same reference point. For other measurement locations similar strain ratios can be obtained as

$$\{\gamma_1, \gamma_2 \ldots\ldots, \gamma_i\} = \left\{\frac{\varepsilon_1}{\varepsilon_R}, \frac{\varepsilon_2}{\varepsilon_R} \ldots\ldots \frac{\varepsilon_i}{\varepsilon_R}\right\} \quad (8)$$

These strain ratios are all independent and remain constant for the same loading configuration with varying amplitude of the applied load.

If the damage of an element is defined as a reduction of the flexural rigidity, the damage can be expressed as follows:

$$E^* I^* = \beta EI \quad (9)$$

where E^*I^* and *EI* are the flexural rigidity of an element under damaged and undamaged state respectively. Here β $(0 \le \beta \le 1)$ is the ratio of the effective flexural rigidity at undamaged condition and intact condition. β is 1 with no damage and zero with complete damage in the element.

The strain at any section x_i from the left support with a damaged element having a reduced stiffness of βEI can be written as

$$\varepsilon_i^* = \frac{R_L x_i y}{\beta EI} \quad (10)$$

The strain ratio between the damaged section and the undamaged reference section can written using Eq. (5) and Eq. (10) as

$$\gamma_i^* = \frac{\varepsilon_i^*}{\varepsilon_R} = \frac{1}{\beta}\frac{x_i}{x_R} \qquad (11)$$

where γ_i^* is the strain ratio between the damaged section and the reference section. From Eqn. (6) and (10) it is obvious that the strain ratio value changes as the measurement location receives any damage.

In practice, it is not always possible to obtain the response of the undamaged structure. Also the numerical model of a structure contains a large number of redundancies and for these reasons non-baseline damage detection techniques have been emerged. The above mentioned technique does not require any reference or previously obtained measurement data to identify or quantify the damage. This technique requires only the sensor configuration information to identify damage if there is any.

2.2 Damage Quantification

From Eqn. (10) the value of β can be obtained as

$$\beta_i = \frac{\chi_i}{\gamma_i} \qquad (12)$$

where $$\chi_i = \frac{x_i}{x_R} \qquad (13)$$

is the location ratio which can be found from the sensor configuration and γ_i^* can be found from the measurement data.

3. NUMERICAL STUDIES ON THE BEAM TYPE STRUTURE

A simple beam type structure was chosen to verify the proposed non-baseline damage identification method through a simulation study. The FE model and the details of the beam are given in Fig.2 and Table 1. The beam is consists of 10 elements and 10 sensors with gage length equal to the size of an element is considered to be installed to measure the average strain over the entire beam element. The success of the proposed damage detection algorithms depends on the measurement of the macro strain. In this section the concept of the macro strain has also been discussed in brief.

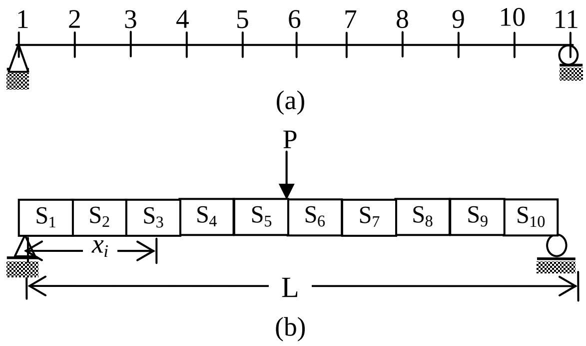


Fig. 2. (a) FE Model of the beam (b) Sensor distribution

Table 1: Properties of the beam

BxH (m)	L (m)	A (m^2)	I (m^4)	E (N/m^2)
0.03x0.01	2.0	0.0003	2.5×10^{-9}	2.1×10^{11}

The average strain or the macro-strain, $\bar{\varepsilon}_i$, over any sensor with a gage length L_i, can be obtained from the rotational displacement with a reasonable assumption that at each element the distance from the inertia axis to the bottom of the beam where sensors are to be installed is the same [8].

$$\bar{\varepsilon}_i = \frac{h_i}{L_i}[\theta_{iR} - \theta_{iL}] \qquad (14)$$

Two reference sensors are considered for the damage identification process. Sensor located at element 1 and element 10 are the reference sensors which are marked as the S_L and S_R respectively. Distances are to be measured from any support to the center of the element. The measured sensor location and the corresponding location ratio w.r.t. the reference sensors are given in Table 2.

The purpose of this simulation study is threefold. First, the study will demonstrate how the damage detection and assessment procedure is organized. Second, the specific application will show more clearly the meaning of some quantities that have been defined by illustrating how they are used. Finally, the simulation results will show how the sensor configuration can be used to obtain the information on the numerical model of the beam or the undamaged state for damage identification and localization.

In Table 2, sensor locations considering two reference sensors are listed. The reference element should be selected in such a way that the probability of receiving any damage to this element is very low. To measure the distance mid point of the element is considered. The location ratios for different elements, χ_i , was calculated using Eq. 12.

Table 2: Sensor location and the corresponding location ratio w.r.t. different sensors

Element	x_{iL} (m)	x_{iR} (m)	χ_{iL}	χ_{iR}
S_1	0.1	1.9	1	19
S_2	0.3	1.7	3	17
S_3	0.5	1.5	5	15
S_4	0.7	1.3	7	13
S_5	0.9	1.1	9	11
S_6	1.1	0.9	11	9
S_7	1.3	0.7	13	7
S_8	1.5	0.5	15	5
S_9	1.7	0.3	17	3
S_{10}	1.9	0.1	19	1

3.1 Damage Scenarios

Five different damage scenarios are considered for the numerical studies. First three cases, C1~C3, considered the undamaged state of the beam. A single point load was applied at different location with varying magnitude on the undamaged beam. The purpose of this part of the study is to show that the ratio of the strains of any element to that of a reference sensor is constant for the undamaged condition of the structure and is equal to the ratio of the location of the same element to that of the same reference sensor. The macro strains of different elements are listed in Tables 4, 5 and 6. Comparison of the strain ratios and the location ratios for cases C1~C3 are shown in Fig. 3.

Cases C4 and C5 show how the proposed method can be applied for damage identification and localization. Two different damage scenarios, single damaged element and multiple damaged elements, are considered to validate the proposed method. Case C4 represents the damage scenario with a single damage at element 5. Damages were introduced by reducing the flexural rigidity of the corresponding element. 10% damage means the 10% stiffness reduction of the element. Another damage scenario with 2 damaged elements, 30% damage to element 4 and 50% damage to element 9, denoted by C5 was considered to simulate the multiple damage case. Details of the studied cases are given in Table 3.

Table 3: Damage scenarios with loading

Case No.	Load Location	Load Value (N)	Damaged Element	Stiffness Reduction (%)
C1	N4	150	None	
C2	N6	50	None	-
C3	N8	100	None	
C4	N9	200	5	10
C5	N7	100	4	30
			9	50

4. RESULTS

In this section the results of the numerical simulation studies are presented. Macro strains obtained from different sensors and corresponding strain ratios for the intact beam are shown in Table 4, 5 and 6. Consider case C3 in which the load was applied at node 8. Strain ratios for the sensors to the left of load point are calculated using the reference sensor located at element 1. Similarly, S_{10} was used to calculate the strain ratios of the sensors located on the right side of the load point. The similar approach is followed to calculate the strain ratio for all other damage scenarios.

Fig.3 shows the strain ratio and the location ratio of the intact beam. Strain ratios and the location ratios have very good agreement and each element has the identical value of location ratio and strain ratios regardless of the loading configuration and/or magnitude. Hence the location ratios can be used to obtain the information on the condition of the intact structure to identify the damage using the strain ratios.

Table 4: Macro strain and corresponding γ_i for C1

Element	Macro Strain (x 10^{-6})	γ_{iL}	γ_{iR}	χ_i
S1	1000.0	1.00	N/A	1.0
S2	3000.0	3.00	N/A	3.0
S3	5000.0	5.00	N/A	5.0
S4	5571.4	N/A	13.0	13.0
S5	4714.3	N/A	11.0	11.0
S6	3857.0	N/A	9.0	9.0
S7	3000.0	N/A	7.0	7.0
S8	2143.0	N/A	5.0	5.0
S9	1285.8	N/A	3.0	3.0
S10	428.5	N/A	1.0	1.0

Table 5: Macro strain and corresponding γ_i for C2

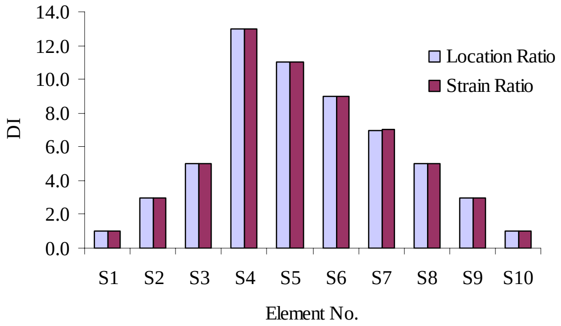
Element	Macro Strain (x 10^{-6})	γ_{iL}	γ_{iR}	χ_i
S1	238.3	1.0	N/A	1.0
S2	714.3	3.0	N/A	3.0
S3	1190.5	5.0	N/A	5.0
S4	1666.7	7.0	N/A	7.0
S5	2142.8	9.0	N/A	9.0
S6	2142.9	N/A	9.0	9.0
S7	1666.7	N/A	7.0	7.0
S8	1190.5	N/A	5.0	5.0
S9	714.3	N/A	3.0	3.0
S10	238.3	N/A	1.0	1.0

Table 6: Macro strain and corresponding γ_i for C3

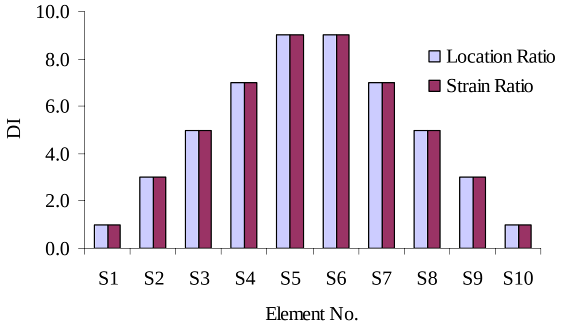
Element	Macro Strain (x 10^{-6})	γ_{iL}	γ_{iR}	χ_i
S_1	285.8	1.00	N/A	1.0
S_2	857.3	3.00	N/A	3.0
S_3	1428.5	5.00	N/A	5.0
S_4	2000.0	7.00	N/A	7.0
S_5	2571.5	9.00	N/A	9.0
S_6	3142.9	11.00	N/A	11.0
S_7	3714.2	13.00	N/A	13.0
S_8	3333.5	N/A	5.00	5.0
S_9	2000.0	N/A	3.00	3.0
S_{10}	666.5	N/A	1.00	1.0

4.1 Single Damage Identification

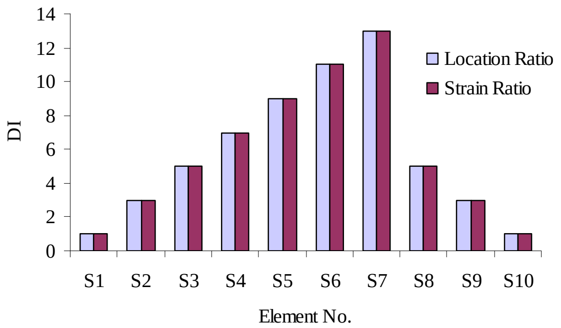
Numerical simulation results for the single damage element case are shown in Table 1. The damage indices of the damaged and intact beam, obtained from the numerical simulation are presented in Fig.4. Damage indices of the damaged beam elements have no change except that of element 5. Since the damage index of the damage inflicted element was changed, damage can easily be identified and localized from the change in damage index of any element.



(a)



(b)



(c)

Fig. 3: Comparison of χ_i and γ_i of intact beam (a) Load case C1 (b) Load case C2 (c) Load case C3

Table 7: Macro strain and corresponding γ_i for C4

Element	Macro Strain (x 10^{-6})	γ_{iL}	γ_{iR}	χ_i
S_1	285.5	1.00	N/A	1.0
S_2	857.0	3.00	N/A	3.0
S_3	1428.3	5.00	N/A	5.0
S_4	1999.8	7.00	N/A	7.0
S_5	2856.5	10.01	N/A	9.0
S_6	3142.2	11.01	N/A	11.0
S_7	3713.6	13.01	N/A	13.0
S_8	4284.8	15.01	N/A	15.0
S_9	3428.0	N/A	3.00	3.0
S_{10}	1142.5	N/A	1.00	1.0

4.2 Multiple Damage Identification

Table 6. shows the macro strain and the corresponding strain ratios for case C3. Since the load was applied at node 7, macro strains of elements 1 to 6 were normalized with the reference sensor located at element 1. Reference sensor located near the right support was used for the rest of the elements macro strain to get the strain ratios. Comparison of the damage indices of the intact beam and the damage beam with 2 damaged elements is shown in Fig. 5. Damage indices of the damaged beam of elements 4 and 9 have different values than that of the intact beam. However, damage indices of other elements have the same values as that of the intact beam.

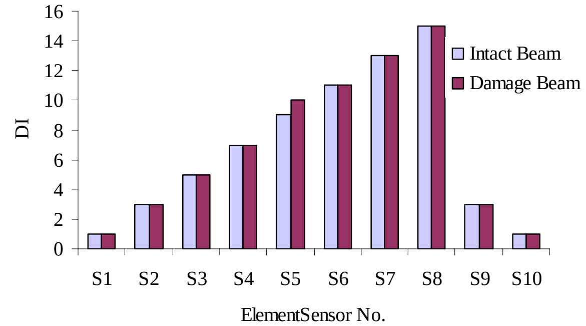


Fig.4: Damage localization for C4

Table 8: Macro strain and corresponding γ_i for C5

Element	Macro Strain (x 10^{-6})	γ_{iL}	γ_{iR}	χ_i
S1	571.3	1.00	N/A	1.0
S2	1714.0	3.00	N/A	3.0
S3	2856.8	5.00	N/A	5.0
S4	5713.0	10.00	N/A	7.0
S5	5141.9	9.00	N/A	9.0
S6	6284.4	11.00	N/A	11.0
S7	5998.8	N/A	7.00	7.0
S8	4285.0	N/A	5.00	5.0
S9	5141.8	N/A	6.00	3.0
S10	857.0	N/A	1.00	1.0

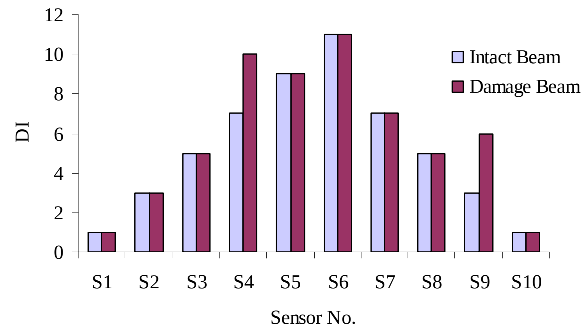


Fig.5: Damage localization for C5

4.3 Damage Quantification

Eq. (12) was used to obtain the reduced stiffness of the damage inflicted element(s). Obtained results are shown in Table 7. The proposed damage index can quantify the low level damage with 10% reduction in flexural rigidity of the damage inflicted element as well as the high level damage with 50% reduction in flexural rigidity.

Table 7: Damage quantification

Damage Case	Damaged Element	Stiffness Reduction (%)	Quantified Damage (%)
C2	5	10	10
C3	4	30	30
	9	50	50

5. CONCLUSIONS

In this paper a non-baseline approach to identify the damage of beam type structures has been presented. To identify the damage it is important to know about the intact condition of the structure. In this paper, a novel technique of damage identification with no need to about the undamaged state or detail numerical model of the structure has been presented. A relation between the damage indices of the undamaged structure and the sensor locations has been derived and verified through numerical case studies. The studied results show that the sensor location ratios w.r.t. a reference location(s) can be used for the damage identification as a base line. The non-baseline damage detection finally illustrated and demonstrated with numerical case studies of a damaged beam. Case study results show that the develop method can detect and assess the damage(s) successfully and accurately. The proposed method will be verified with experimental case studies with the application of long-gage distributed fiber optic sensor.

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7. NOMENCLATURE

Symbol	Meaning	Unit
A	Section Area	(m^2)
DOF	Degrees of freedom	
E	Modulus of Elasticity	(N/m^2)
I	Moment of Inertia	(Pa)
χ_i	Location ratio of the sensor	
γ_i	Strain ratios of the intact beam	
β	Remaining stiffness	
$\bar{\varepsilon}_i$	Average strain of the *i*th element	
θ_{iR}	Rotation of *i*th element at right node	(Radians)
θ_{iL}	Rotation of *i*th element at left node	(Radians)

Symbols with the * mark represent the same meaning for the damaged structure