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Multimetric Sensing for Structural Damage Detection

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ABSTRACT

Vibration-based damage detection methods have been widely studied for structural health monitoring of civil infrastructure. Acceleration measurements are frequently employed to extract the dynamic characteristics of the structure and locate damage, because they can be obtained conveniently and possess relatively little noise. However, considering the fact that damage is a local phenomenon, the sole use of acceleration measurements that are intrinsically global structural responses limits damage detection capabilities. This paper investigates the possibility of using both global and local measurements to improve the accuracy and robustness of damage detection methods. A multimetric approach based on the damage locating vector (DLV) method is proposed. Numerical simulations are conducted to verify the efficacy of the proposed approach.

Keywords: multimetric sensing, structural health monitoring, damage detection, damage locating vector method

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1 INTRODUCTION

With the realization of the potential of structural health monitoring (SHM) as an effective tool to manage civil infrastructures, extensive research has been conducted, producing a wide variety of SHM techniques. Thorough reviews of the advances in SHM in the last few decades have been provided by Doebling *et al*. (1996) and Sohn *et al*. (2003). In particular, vibration-based damage detection methods have been widely adopted for SHM. With the current progress in smart sensor research exploiting wireless communication and data processing capabilities of sensor nodes, dense measurements of structural vibration are considered feasible in the near future. Acceleration is frequently the preferred measurand due to the convenience of installation of accelerometers and their relatively high signal-to-noise ratio. Acceleration signals are considered to contain information regarding the global behavior of structures. However, knowing damage is a local phenomenon, damage localization using only global measurements has its limitations.

Multimetric sensing using a heterogeneous mix of measurands at various scales has the potential to provide for more accurate characterization of the state of a structure. Recently, research effort has been increasingly devoted to the development of multimetric sensing strategies for structural health monitoring (Gangone *et al*., 2007; Mugambi *et al*., 2007). Studer and Peters (2004) presented a damage identification approach for composite structures using multimetric data that are strain, integrated strain, and strain gradients measured from optical fiber sensors. Law *et al*. (2005) used a wavelet-based approach to combine acceleration and strain responses to obtain better damage detection results than using the two measurements separately. Based on these results, Kijewski-Correa *et al*.

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(2006) developed a decentralized SHM strategy that uses measured strain and acceleration and can be implemented on a wireless sensor network. A signal-based damage detection scheme based on the two-stage AR-ARX method developed at Los Alamos National Laboratory (Sohn and Farrar 2001) is employed in the sensor network. However, this method does not exploit spatial information that potentially improves damage detection and localization. To fully utilize the spatial information in the inherent distributed computing environment offered by smart sensors, effort is required to develop effective multimetric damage detection strategies that can be applied to a broad class of structures.

The flexibility-based damage locating vector (DLV) method proposed by Bernal (2002) has been shown to be a promising damage detection approach for SHM. Unlike the stiffness matrix, the flexibility matrix is insensitive to higher frequency modes that are normally difficult to determine from measured data (Gao *et al*. 2004). Gao *et al*. (2005) and Gao and Spencer (2008) developed a distributed computing strategy based on the DLV method that can be implemented on a dense array of sensor such as will be needed to effectively monitor large civil infrastructure. Nagayama and Spencer (2007) realized this distributed computing strategy on a network of smart sensors using the Imote2. The DLV method has been shown to be quite effective and versatile for deployment on smart sensor networks.

This paper presents a damage detection approach employing multimetric sensing that builds off of the work of Bernal (2002), Gao *et al*. (2005), and Nagayama and Spencer (2007). In particular, the stochastic DLV method (Bernal 2006) will be extended to utilize

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strain and acceleration in combination. Numerical simulations are presented to verify the efficacy of the proposed method.

2 DAMAGE LOCATING VECTOR METHOD

2.1 *DLV method*

For completeness, the DLV method is briefly reviewed in this section. The flexibility matrices of a linear structure before and after damage are determined from the measured data and are denoted as F_u and F_d, respectively. Assume the load vectors L that produce identical displacements at the sensor locations before and after damage exist and can be written as

$$(F_u - F_d) \cdot L = F_\Delta \cdot L = 0 \tag{1}$$

These vectors, L, are termed the damage locating vectors (DLVs). The DLVs constitute a set of loads that induce no stress in the damaged elements. Excluding the trivial case where $F_\Delta = 0$, L is in the null space of F_Δ and can be determined using the singular value decomposition.

Once determined, each of the DLVs can be applied to a numerical model of the undamaged structure, and the stress in each element calculated and normalized as follows:

$$\bar{\sigma}_j = \frac{\sigma_j}{\max\limits_k (\sigma_k)} \quad \text{and} \quad \sigma_j = \sum_{i=1}^{m} \text{abs}\left(\frac{\sigma_{ij}}{\max\limits_k (\sigma_{ik})} \right) \tag{2}$$

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where σ_j is the normalized accumulated stress, σ_{ij} is the stress in the *j*th element induced by the *i*th DLV, and *m* is the number of DLVs. If the normalized stress in an element is zero, then this element is a damage candidate. However in practice, the cumulative stress may not be exactly zero due to intrinsic uncertainties such as measurement noise or model error. Thus, a threshold value needs to be selected to determine the damaged elements. If the cumulative stress of an element is less than the selected threshold, then the element is considered as a damage candidate. This nonzero error stress at the damaged element caused by uncertainties is required to be small for reliable damage detection.

2.2 *Stochastic DLV method*

Bernal (2006) extended the DLV method to accommodate the output-only case (*i.e.*, the input excitation is not measured), resulting in the stochastic DLV method. In this approach, an alternative matrix that spans the same null space as F_Δ in Eq. (1) is used to determine the DLVs. The stochastic DLV method has been extended, implemented, and experimentally verified on a network of smart sensors (Nagayama and Spencer 2007). In the next section, the stochastic DLV method is further extended to accommodate multimetric sensed data.

3 DERIVATION

The DLV method and the flexibility matrix estimation are based on global measurements such as displacement, velocity, and acceleration. Only accelerations have been used in the

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experimental verification of the DLV method (Gao *et al*. 2004; Spencer and Nagayama 2006). This section presents an approach to combine the strain with the displacement, velocity, and acceleration in the stochastic DLV method.

3.1 *Strain flexibility matrix*

Consider the flexibility matrix F_d that relates the external load to the displacement of the structure such that

$$\{u\} = F_d \{L\} \tag{3}$$

where $\{u\}$ and $\{L\}$ are the displacement and load vectors, respectively. The strain flexibility F^* is defined herein as

$$\{\varepsilon\} = F^* \{L\} \tag{4}$$

where $\{\varepsilon\}$ is the strain vector. Assume that a linear transformation T between the strain and the displacement exists such that

$$\{\varepsilon\} = T \{u\} \tag{5}$$

The strain flexibility matrix is then written as:

$$F^* = TF_d \tag{6}$$

In terms of the modal parameters, the flexibility matrix and the strain flexibility matrix can be expressed as

$$F_d = \Phi_d D \Phi_d^{\mathrm{T}} \tag{7}$$

$$F^* = TF_d = T\Phi_d D \Phi_d^{\mathrm{T}} = \Phi_s D \Phi_d^{\mathrm{T}} \tag{8}$$

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where Φ_d is the displacement mode shape matrix, Φ_s is the strain mode shape matrix, and

$$D = diag\left(\left[\left(d_1/\omega_1\right)^2 \quad \left(d_2/\omega_2\right)^2 \quad \cdots \quad \left(d_j/\omega_j\right)^2 \quad \cdots\right]\right) \tag{9}$$

where d_j and ω_j are the mass normalization constant and the natural frequency of the jth mode, respectively. Eq. (8) shows that the strain flexibility matrix is not symmetric in the definition given in Eq. (4), while the stochastic DLV method requires the symmetry of the flexibility matrix (Bernal 2006).

This difficulty can be overcome by introducing the pseudo element force vector $\{L_e\}$ such that

$$\{L\} = T^{\mathrm{T}}\{L_e\} \tag{10}$$

Note that for statically determinate structures, the pseudo element force $\{L_e\}$ is equal to the element force. Then the strain flexibility relating the strain and the pseudo element force can be defined as:

$$\{\varepsilon\} = F_s\{L_e\} \tag{11}$$

Substituting Eqs. (3), (5), and (10) into Eq. (11),

$$F_s\{L_e\} = TF_dT^{\mathrm{T}}\{L_e\} \tag{12}$$

For an arbitrary force $\{L_e\}$, Eq. (12) is satisfied if and only if

$$F_s = TF_dT^{\mathrm{T}} \tag{13}$$

or in terms of the modal parameters

$$F_s = T\left(\Phi_d D \Phi_d^{\mathrm{T}}\right)T^{\mathrm{T}} = \Phi_s D \Phi_s^{\mathrm{T}} \tag{14}$$

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Thus, the symmetry of the strain flexibility defined in Eq. (11) is ensured.

The flexibility matrix including both displacement and strain can be shown to be symmetric as follows. Consider a system under two load vectors, L_1 in the coordinate where displacements are defined, and L_2 which is a pseudo element force. The displacement and strain are thus

$$u = FL_1 + FT^{\mathrm{T}} L_2 \tag{14}$$

$$\varepsilon = Td = TFL_1 + TFT^{\mathrm{T}} L_2 \tag{14}$$

which leads to the combined flexibility matrix such that

$$\begin{bmatrix} u \\ \varepsilon \end{bmatrix} = \begin{bmatrix} F & FT^{\mathrm{T}} \\ TF & TFT^{\mathrm{T}} \end{bmatrix} \begin{bmatrix} L_1 \\ L_2 \end{bmatrix} \tag{14}$$

The symmetry of the combined flexibility matrix enables the use of multimetric data in the stochastic DLV method.

3.2 *Multimetric data in the stochastic DLV method*

The formulation in this section follows the derivation of the stochastic DLV method (Bernal 2006), but extends the approach to accommodate the combined use of strain and acceleration. Consider a system represented in the following state space form

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= C_d x + D_d u \end{aligned} \tag{15}$$

where y is the displacement vector, $C_d \in R_{m\times N}$, $D_d \in R_{m\times n}$, N is the order of the system, m and n are the numbers of displacements and inputs, respectively. Because the input force is

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not directly transmitted to the displacement, $D_d = 0$. Taking the first and second derivatives of the output in Eq. (15) yields

$$\dot{y} = C_d A x + C_d B u \tag{16}$$

$$\ddot{y} = C_d A^2 x + C_d A B u + C_d B \dot{u} \tag{17}$$

The fact that the input force is not directly transmitted to the velocity leads to

$$C_d B = 0 \tag{18}$$

In addition, the output and direct transmission matrices for the acceleration in Eq. (18) can be written as:

$$C_a = C_d A^2 \tag{19}$$

$$D_a = C_d A B \tag{20}$$

Substituting C_d in Eq. (19) into Eqs. (18) and (20),

$$C_a A^{-2} B = 0 \tag{21}$$

$$C_a A^{-1} B = D_a \tag{22}$$

For velocity and displacement, similar equations can be derived as (Bernal 2006)

$$C_v A^{-1} B = C_d B = 0 \tag{23}$$

$$C_v B = C_d A B = D_a \tag{24}$$

where C_v and C_d are the output matrices for velocity and displacement. The output matrix $C_s \in R_{l \times N}$ for the strain where l is the number of strains is introduced by multiplying Eqs. (18) and (20) by the transform matrix T in Eq. (5) to obtain

$$T C_d B = C_s B = 0 \tag{25}$$

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$$TD_a = TC_d AB = C_s AB \tag{26}$$

Eqs. (21) ~ (26) can be combined in a simple form as

$$H_{pm} B = L_h D_a \tag{27}$$

where $H_{pm} \in R_{2(m+l)\times N}$ and $L_h \in R_{2(m+l)\times m}$ are given by

$$H_{pm} = \begin{bmatrix} C_c A^{1-p} \\ C_s A \\ C_c A^{-p} \\ C_s \end{bmatrix} \text{ and } L_h = \begin{bmatrix} I_{m\times m} \\ T_{l\times m} \\ 0_{m\times m} \\ 0_{l\times m} \end{bmatrix} \tag{28}$$

where $p = 0,1$, and 2 for displacement, velocity and acceleration, respectively, and C_c is the corresponding output matrix. The input matrix B in Eq. (27) is then written as:

$$B = H_{pm}^{+} L_h D_a \tag{29}$$

where H_{pm}^{+} is the pseudo inverse (Penrose 1955) of H_{pm}.

The flexibility matrix can be determined (Bernal and Gunes 2004) as

$$F_p = -C_p A_p^{-(p+1)} B_p \tag{30}$$

The combined flexibility matrix is:

$$F = -\begin{bmatrix} C_c A^{-(p+1)} \\ C_s A^{-1} \end{bmatrix} \begin{bmatrix} B & BT^T \end{bmatrix} = Q_m D_m \tag{31}$$

where:

$$Q_m = -\begin{bmatrix} C_a A^{-(p+1)} \\ C_s A^{-1} \end{bmatrix} H_{pm}^{+} L_h \tag{32}$$

$$D_m = D_a \begin{bmatrix} I & T^T \end{bmatrix} \tag{33}$$

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Subtracting the flexibility matrices from the damaged and undamaged states,

$$F_d - F_u = Q_{m,d} D_{m,d} - Q_{m,u} D_{m,u} \tag{34}$$

where the subscripts d and u denote damaged and undamaged states. Introducing $\Delta D_m = D_{m,d} - D_{m,u}$, $\Delta Q_m = Q_{m,d} - Q_{m,u}$ and $\Delta F = F_d - F_u$, Eq. (40) becomes

$$\Delta F = \Delta Q_m D_{m,u} - Q_{m,d} \Delta D_m \tag{35}$$

Performing the singular value decomposition, ΔD_m can be written as

$$\Delta D_m = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \begin{bmatrix} s_1 & 0 \\ 0 & s_2 \end{bmatrix} \begin{bmatrix} Z_1^T \\ Z_2^T \end{bmatrix} \tag{36}$$

Assuming that the singular value s_2 is negligible, post-multiplying Z_2 to Eq. (41) yields

$$\Delta F \cdot Z_2 \simeq \Delta Q_m D_{m,u} Z_2 \tag{37}$$

Taking the transpose of Eq. (43) leads to the fundamental expression for the stochastic DLV method:

$$\left(Z_2^T\right) \Delta F \simeq \left(Z_2^T D_{m,u}\right) \Delta Q_m{}^T \tag{38}$$

Because most vectors in the null space of ΔQ_m^T will be in the near null space of the change in the flexibility matrix (Bernal 2006), Q_m can be employed as a substitute for the flexibility matrix. The singular value decomposition of ΔQ_m^T leads to the DLVs.

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3.3 *DLV from multimetric data*

The damage locating vectors obtained using the singular value decomposition consist of two parts corresponding to displacement and strain. The combined damage locating vector $\{L_c\}$ is written as:

$$\{L_c\} = \begin{bmatrix} \{L_1\} \\ \{L_2\} \end{bmatrix} \tag{39}$$

where $\{L_1\}$ and $\{L_2\}$ are the load vectors for displacement and strain, respectively. To apply $\{L_2\}$ to the structural model, $\{L_2\}$ needs be converted as $\{L_n\} = T^T\{L_2\}$. Note that the load vectors $\{L_1\}$ and $\{L_n\}$ are not necessarily applied at co-located or separately located nodes; they can share none, some, or all of the nodes. Applying the load vectors, the normalized accumulated stress can be obtained using Eq. (2).

If only strain measurements are used in damage detection, the stochastic DLV method requires the strain in the damaged element to be measured. For statically determinate structures, the pseudo element force $\{L_2\}$ is equal to the element force, resulting in zero stress at the unmeasured elements regardless of the damage status of the elements. For redundant structures, although the stress induced by $\{L_2\}$ is redistributed over the adjacent elements, the redistributed stress is generally not significant when compared to the stress induced by $\{L_2\}$. Due to the small stress, the damage localization in an unmeasured element is difficult in practice. This limitation on the use of strain measurement for damage detection can be resolved by using acceleration along with strain, as will be demonstrated in the next section.

4 NUMERICAL VALIDATION

4.1 *Overview of simulation*

Numerical simulation is conducted to verify the efficacy of the proposed extension of the stochastic DLV method using multimetric data. Consider the 53 degree-of-freedom (DOF) planar truss model shown in Figure 1. Damage is simulated by 10% and 40% stiffness reductions in element 16. Independent band-limited white noise forces are applied as the input excitation in both horizontal and vertical directions at all nodes. Vertical and horizontal accelerations are measured at nodes 5~7 and 19~21 and the strain is measured at elements 16~25. Gaussian measurement noise with a bandwidth up to the Nyquist frequency and an amplitude of 5% RMS the corresponding measured signal is added to the acceleration and strain. Because these nodes and elements are in the fourth and fifth bays of the truss model, only the elements in these bays (elements 16~25) are considered in damage detection (Gao *et al*. 2005). Note that the structural model is internally statically indeterminate because of these bays.

Simulation cases in Table 1 are considered for both the 10% and 40% damage: (a) Case 1: strain-only, (b) Cases 2~5: acceleration-only, (c) Cases 6~10: Multimetric data when strain in the damaged element is measured, and (d) Cases 11~15: Multimetric data without measuring strain in the damage element. Each simulation case is repeated 500

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times independently to account for the statistical nature of the problem while investigating the accuracy and robustness of the proposed method.

The mean and standard deviation of the normalized accumulated stress for cases 1 (strain-only), 3 (acceleration-only), and 10 (multimetric) are shown in Figure 2. As can be seen in these figures, the normalized accumulated stress in element 16 is considerably smaller than other elements of interest. Therefore, the stochastic DLV method identifies element 16 as a damage candidate in these cases. The normalized accumulated stress at element 16 for Case 10 (*i.e.*, multimetric data) has a smaller mean value and less variation than that for Case 2 (*i.e.*, acceleration-only). Although Case 1 (*i.e.,* strain-only) has the smallest stress at element 16, the strain in the damaged element should be measured, as previously illustrated. As such, multimetric data is seen to reduce the normalized accumulated stress at damage location, as well as facilitate the use of strain in the stochastic DLV method. More detailed discussion follows in the remainder of this section.

4.2 Performance evaluation: false negative and false positive detections

False negative and false positive detections of damage are considered to demonstrate the efficacy of the proposed multimetric sensing approach. A false negative detection occurs when the algorithm cannot detect a damaged element, *i.e.*, reports it as undamaged. A false positive detection occurs when the algorithm reports an undamaged element as damaged. From the structural engineering perspective, the false negative detection is more critical, because undetected damaged elements may have severe consequences, even resulting in structural collapse. On the other hand, false positive detections can needlessly heighten

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concern about a safe structure. Note that in the DLV method the zero stress does not necessarily mean damage; the term 'damage candidate' is used. Practically, when damage candidate elements are identified based on the threshold stress, further actions should be taken to verify damage and repair if necessary. Thus, the false positive detection is defined to evaluate how often false *damage candidates* are identified. For the simulations reported herein, the numbers of false negative and positive detections are tracked.

Figure 3 shows the percentage of false negative detections for 10% stiffness reduction for the cases (a) only strain or only acceleration, (b) multimetric data when strain in the damaged element is measured, and (c) multimetric data when strain in the damaged element is not measured. Compared to the acceleration-only cases (Cases 2~5), the false detection rate is drastically reduced if multimetric data is employed. In particular, the false detection of all acceleration-only cases is nearly 100% (see Figure 3a), which is shown to be significantly reduced by the use of multimetric data (see Figure 3b, c). Note that the strain-only case (Case 1) has a smaller number of false negatives than the acceleration-only cases (see Figure 3a). However, the strain-only case has a critical limitation, as described in the previous section, that strain in the damaged element must be measured to localize damage.

While multimetric data can reduce the false negative detection, multimetric data does not always guarantee a smaller number of false positives than for the case when strain or acceleration is used separately. In cases 8, 11, and 12 of Figure 4, the number of false positive detections is greater than for the case when only accelerations were used (*e.g.*, Case 4). Because false negative detection is more critical than false positive detection, use

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of multimetric data is considered to be more effective than use of either strain or acceleration separately. By selecting a proper threshold stress, both the false positive and negative detections can be reduced to an acceptable level.

The 40% stiffness reduction case shows the same trend as in the 10% case. The false negative detection rates are significantly reduced when the multimetric data is employed as can be seen in Figure 5 while the false positive detection rates tend to increase in Figure 6.

Note that when strain at the damaged element is not measured (Case 11~15), the numbers of false negative detections in Figures 3c and 5c are somewhat greater than for the cases when it is measured (Case 10~13) in Figures 3b and 5b, showing seemingly better performance. However, the damage decision for non-measured elements becomes less reliable, because the DLV obtained using strain data is applied only to the measured elements, making the cumulative stress at the unmeasured elements smaller when normalized. Thus, unmeasured elements have a higher chance of false positive detections as shown in Figures 4 and 6. Although the smaller number of false negative detections is considered normally better, false positive detection also should be taken into account to appropriately assess structural damage.

Damage detection results from numerical simulation have been presented in this section to evaluate the performance of the proposed approach utilizing multimetric data for structural damage detection. Two different damage severity cases (10% and 40% stiffness reductions at a horizontal element) have been considered. Damage at a diagonal element has produced the similar trend as in the horizontal element although it is not presented

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herein due to space limitations. From the numerical study, multimetric data has been shown to improve the performance of structural damage detection.

5 CONCLUSIONS

A damage detection approach based on the stochastic DLV method using the multimetric data has been proposed. A symmetric strain flexibility matrix was introduced, and the stochastic DLV method was modified to accommodate acceleration and strain measurements simultaneously. The proposed approach was validated by conducting extensive numerical simulation using a planar truss model.

The proposed multimetric data damage detection strategy outperformed the stochastic DLV method using only a single type of data in the numerical simulation studies. In particular, the limitation of the strain-only case that the strain in the damaged element needs to be measured was resolved with the aid of acceleration. This result shows the proposed multimetric damage detection strategy is promising for SHM. Experimental verification of the proposed approach is currently underway.

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Figure caption list

Figure 1. 53 DOF planar truss model.

Figure 2. Mean and standard deviation of normalized accumulated stress (40% stiffness reduction in element 16).

Figure 3. False negative detection (10% stiffness reduction).
(a) Strain and acceleration employed independently.
(b) Multimetric data when strain in the damaged element is measured.
(c) Multimetric data without measuring strain in the damage element.

Figure 4. False positive detection (10% stiffness reduction).
(a) Strain and acceleration employed independently.
(b) Multimetric data when strain in the damaged element is measured.
(c) Multimetric data without measuring strain in the damage element.

Figure 5. False negative detection (40% stiffness reduction).
(a) Strain and acceleration employed independently.
(b) Multimetric data when strain in the damaged element is measured.
(c) Multimetric data without measuring strain in the damage element.

Figure 6. False positive detection (40% stiffness reduction).
(a) Strain and acceleration employed independently.
(b) Multimetric data when strain in the damaged element is measured.
(c) Multimetric data without measuring strain in the damage element.

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Table 1. Simulation cases.

Case	Acceleration		Strain		
	Number of measurements	Node	Number of measurements	Element	Strain in the damaged element measured?
1	0	N/A	11	15~25	Y
2	10	5~7, 19, 20	0	N/A	N
3	12	5~7, 19~21	0	N/A	N
4	14	4~7, 19~21	0	N/A	N
5	16	4~7, 18~21	0	N/A	N
6	12	5~7, 19~21	1	16	Y
7	12	5~7, 19~21	3	16, 23, 24	Y
8	12	5~7, 19~21	6	16, 20, 22~25	Y
9	12	5~7, 19~21	8	16, 18, 20~25	Y
10	12	5~7, 19~21	11	15~25	Y
11	12	5~7, 19~21	1	17	N
12	12	5~7, 19~21	3	15, 17, 19	N
13	12	5~7, 19~21	6	15, 17~21	N
14	12	5~7, 19~21	8	15, 17~22, 25	N
15	12	5~7, 19~21	10	15, 17~25	N

Figure Caption List

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Figure 1. 53 DOF planar truss model.

Figure 2. Mean and standard deviation of normalized accumulated stress (40% stiffness reduction in element 16).

Figure 3. False negative detection (10% stiffness reduction).

(a) Strain and acceleration employed independently.

(b) Multimetric data when strain in the damaged element is measured.

(c) Multimetric data without measuring strain in the damage element.

Figure 4. False positive detection (10% stiffness reduction).

(a) Strain and acceleration employed independently.

(b) Multimetric data when strain in the damaged element is measured.

(c) Multimetric data without measuring strain in the damage element.

Figure 5. False negative detection (40% stiffness reduction).

(a) Strain and acceleration employed independently.

(b) Multimetric data when strain in the damaged element is measured.

(c) Multimetric data without measuring strain in the damage element.

Figure 6. False positive detection (40% stiffness reduction).

(a) Strain and acceleration employed independently.

(b) Multimetric data when strain in the damaged element is measured.

(c) Multimetric data without measuring strain in the damage element.

Figure 1

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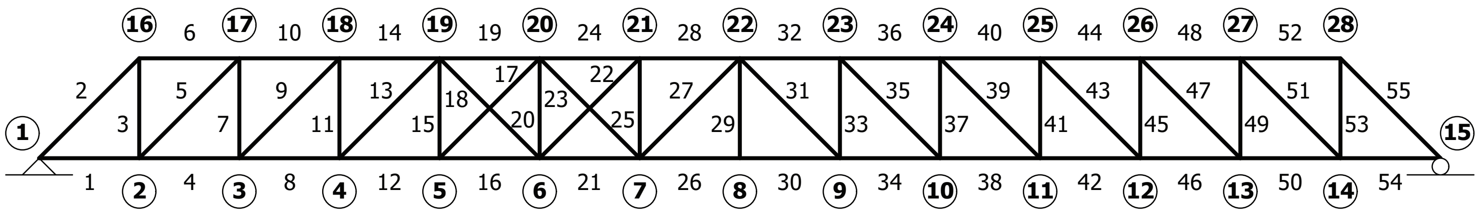

Figure 2

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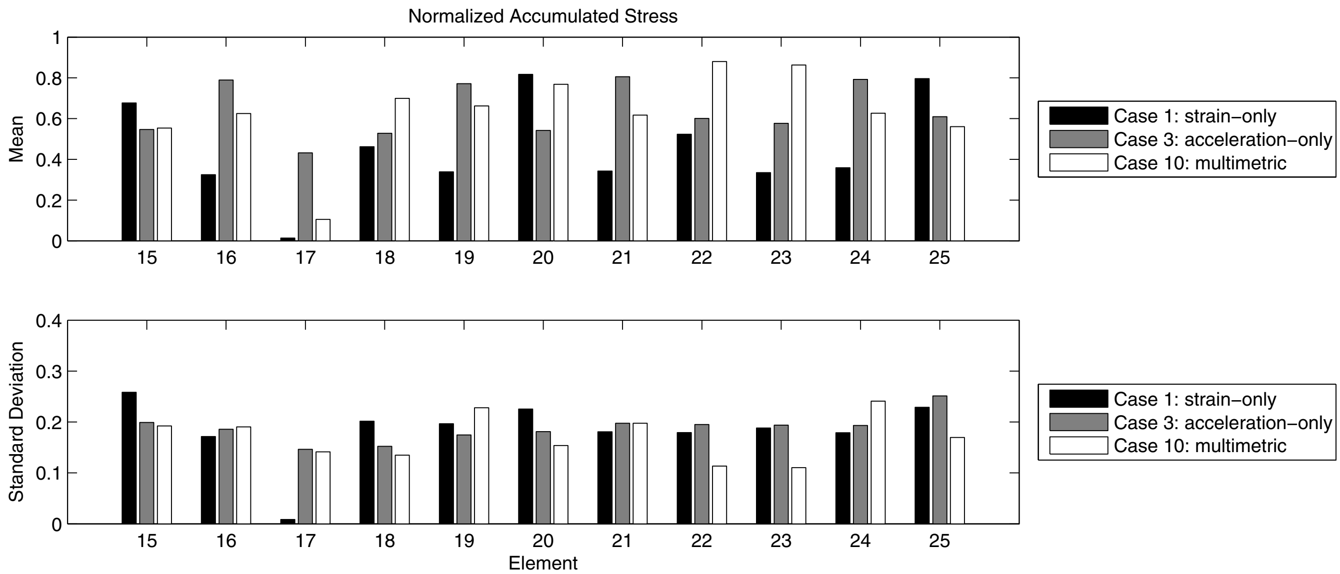

Figure 3a

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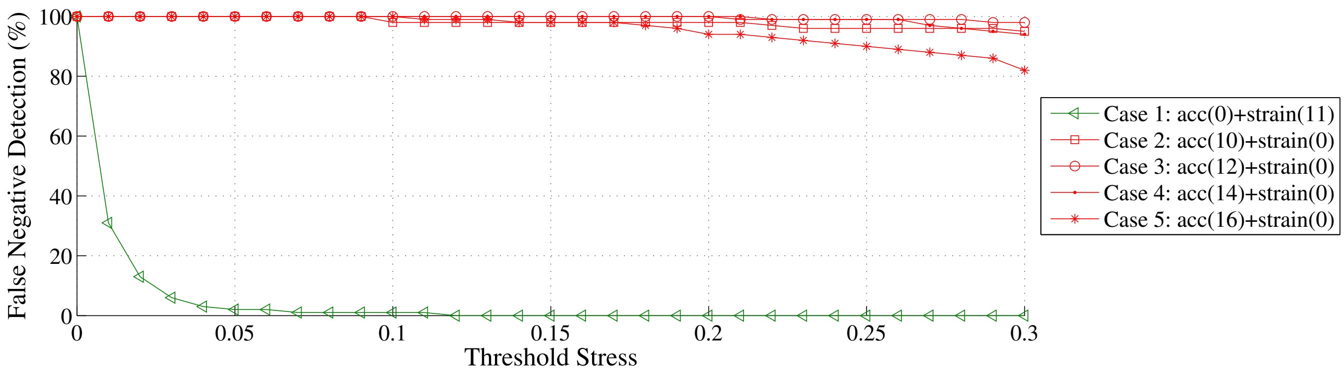

Figure 3b

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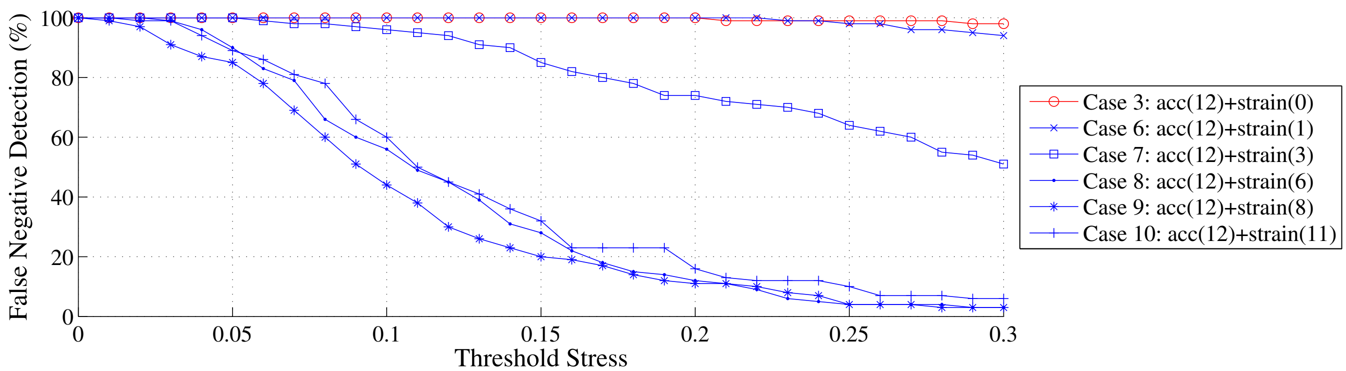

Figure 3c

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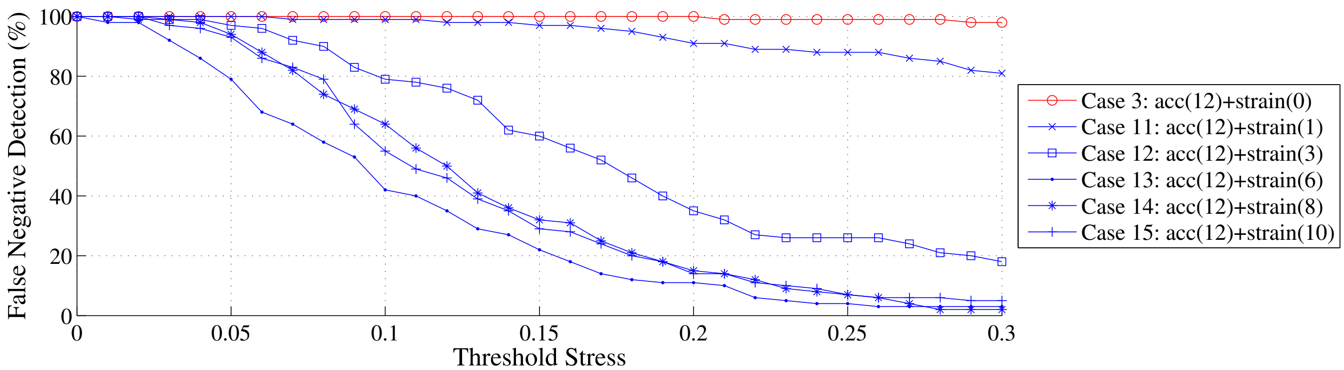

Figure 4a

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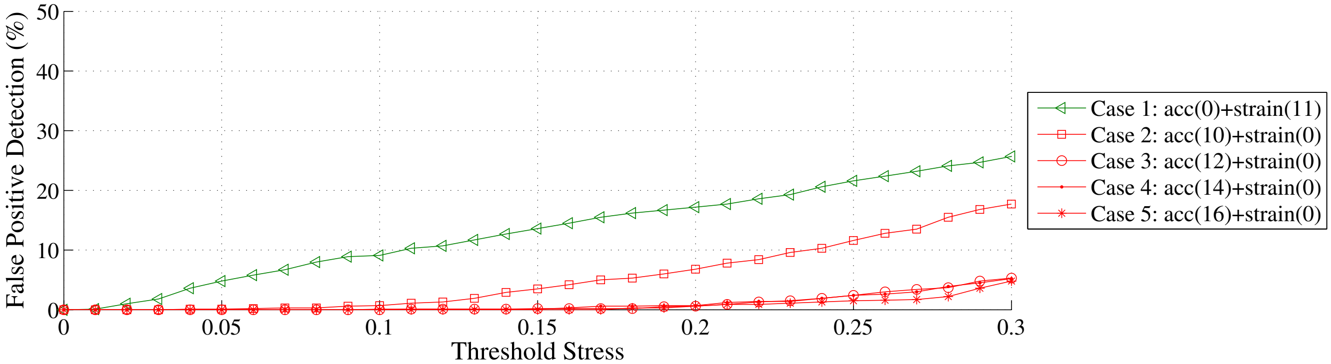

Figure 4b

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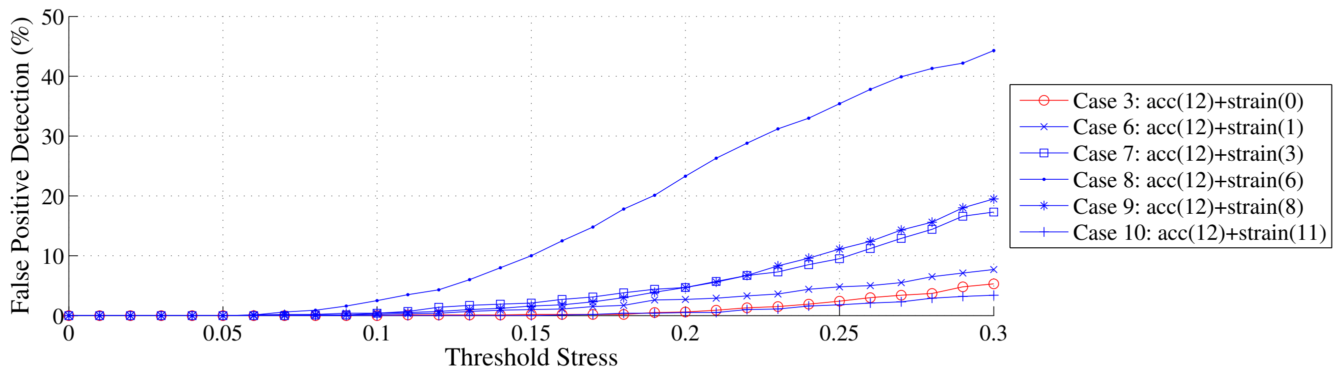

Figure 4c

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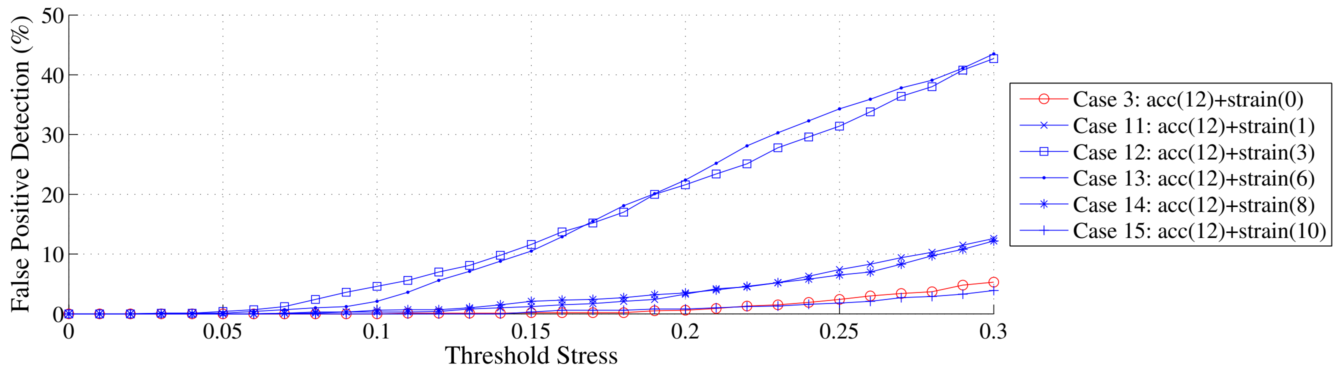

Figure 5a

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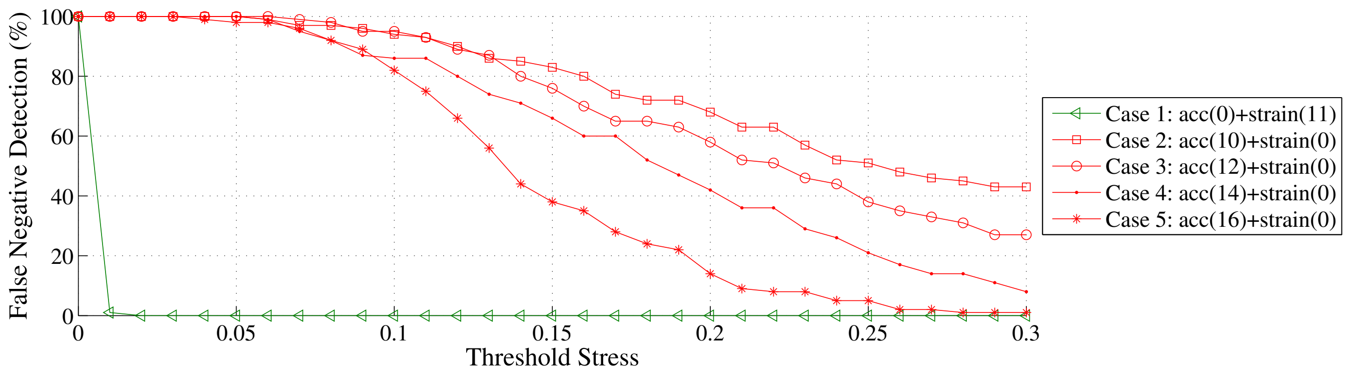

Figure 5b

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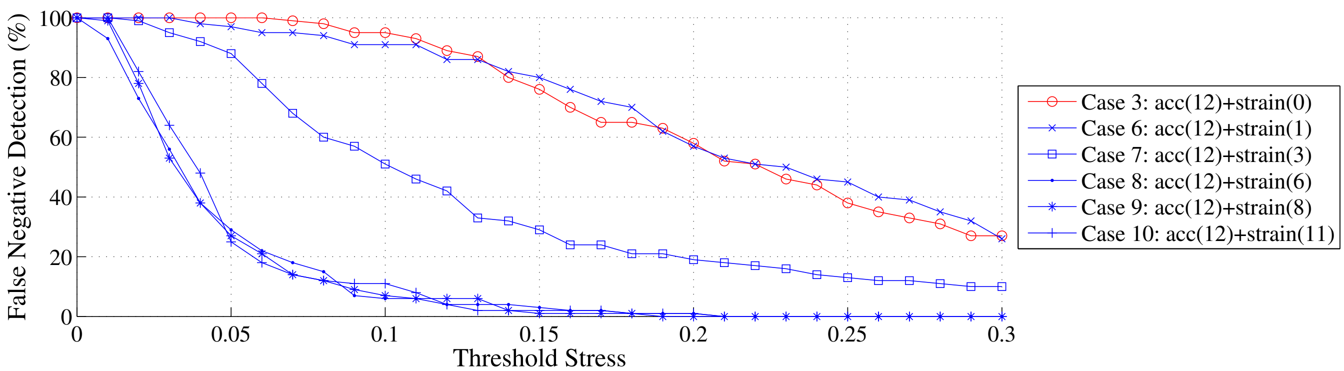

Figure 5c

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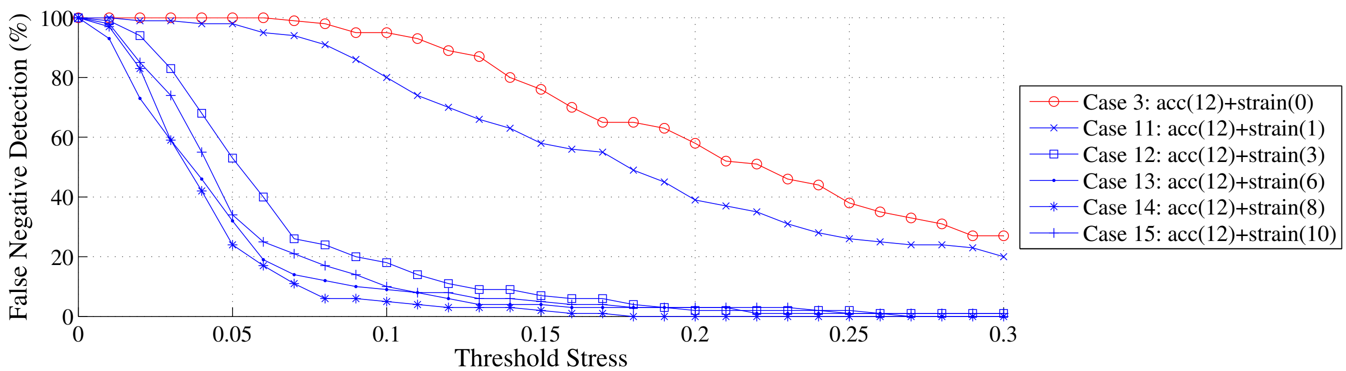

Figure 6a

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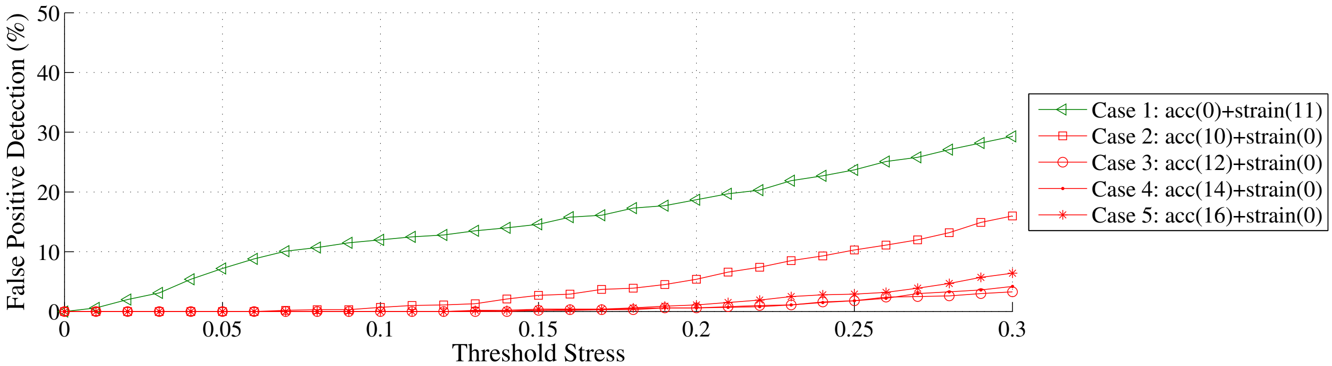

Figure 6b

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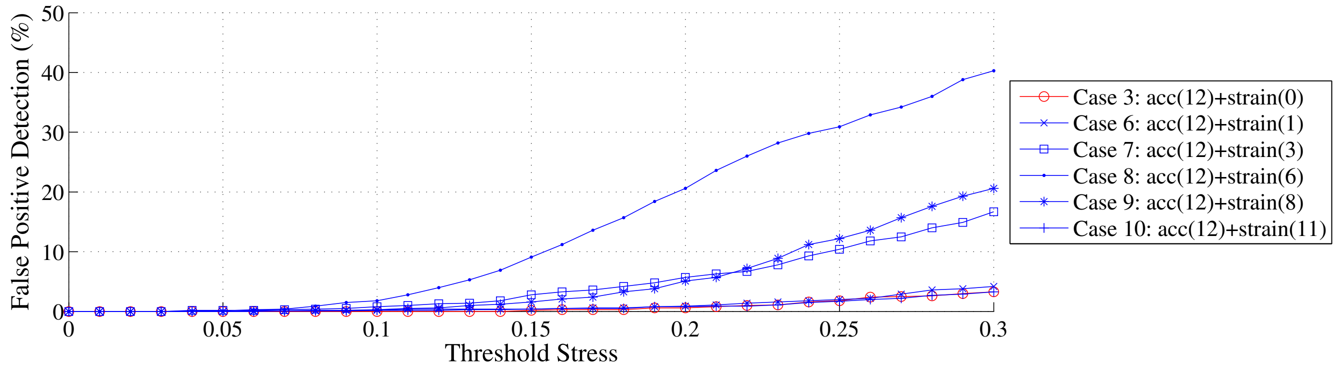

Figure 6c

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