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A fast damage detecting technique for indeterminate trusses

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Abstract. Detecting the damage of indeterminate trusses is of major importance in the literature. This paper proposes a quick approach in this regard, utilizing a precise mathematical approach based on Finite Element Method. Different to a general two-step method defined in the literature essentially based on optimization approach, this method consists of three steps including Damage-Suspected Element Identification step, Imminent Damaged Element Identification step, and finally, Damage Severity Detection step and does not need any optimizing algorithm. The first step focuses on the identification of damage-suspected elements using an index based on modal residual force vector. In the second step, imminent damage elements are identified among the damage-suspected elements detected in the previous step using a specific technique. Ultimately, in the third step, a novel relation is derived to calculate the damage severity of each imminent damaged element. To show the efficiency and quick function of the proposed method, three examples including a 25-bar planar truss, a 31-bar planar truss, and a 52-bar space truss are studied; results of which indicate that the method is innovatively capable of suitably detecting, for indeterminate trusses, not only damaged elements but also their individual damage severity by carrying out solely one analysis.

Keywords: damage detection; indeterminate trusses; Finite Element Method; residual force vector-based index

1. Introduction

Damage detection is a serious issue in structural engineering because structures during their service life may be locally damaged for various reasons, such as fire, fatigue, storm, earthquake, poor maintenance, etc.

The process of applying a damage detection strategy for a structure is referred to as Structural Health Monitoring abbreviated SHM. Usage Monitoring (UM) tries to measure the inputs and responses of a structure before damage so that regression analysis can be used for forecasting the beginning of damage in the structure. Prognosis is the combination of the information obtained from SHM, UM, current environmental and operational conditions, previous component and structural system level testing, and numerical modeling to estimate the remaining useful life of the structure (Sohn *et al*. 2004).

Mathematically, structural damage identification problems are highly non-linear and many special approaches have been employed till now to properly solve them. Optimization approach is one of these approaches. In this approach, damage identification problem is converted to one based on optimization, in which the damage severity of each structural element is considered a design variable (Meruane and Heylen 2011, Kang *et al*. 2012, Kaveh and Maniat 2015, Xu *et al*. 2015, Kaveh *et al*. 2016, Xu *et al*. 2016, Nobahari *et al*. 2017a, Gomes *et al*. 2019a, Gomes *et al*. 2019b). Although this method enables us to identify the damage of structures, because of numerous design variables, it requires many computational attempts. Therefore, two-stage techniques were introduced and developed to diminish the computational cost of optimization process by decreasing the number of design variables via eliminating healthy members (Yun *et al*. 2009, Guo and Li 2009, Cury *et al*. 2010, Jiang *et al*. 2011, Guo 2011, Seyedpoor 2012, Xiang and Liang 2012, Nobahari and Seyedpoor 2013, Ghasemi *et al*. 2018, Nobahari *et al*. 2019). In the first stage of these techniques, an indicator is usually presented to identify damage-suspected elements. In the second stage, an optimization algorithm, such as Particle Swarm Optimization algorithm (PSO), is employed to find the damage severites of these elements.

Modal Residual Force Vector (MRFV) has been widely used in the first phase of two-stage techniques by many researchers for the identification of damage-suspected structural elements. Yang and Liu 2007 studied structural damage identification methods based on residual force vector. Using residual force vector, nodal residual force vector was defined to locate damage-suspected elements preliminarily. Then, three damage quantification techniques including the algebraic solution of the residual force equation, MREU technique, and natural frequency sensitivity method were studied to identify damage more precisely. For localizing and quantifying the structural damage in shear frames, Ghodrati Amiri *et al*. 2013 proposed two damage detection methods; one of which was devoted to detecting structural damage by modal residual force. Seyedpoor and Montazer 2016 proposed a two-stage method for the damage detection in truss systems. In the first stage, damage-suspected elements were found by an

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indicator based on modal residual vector to reduce the damage variables of the truss structure. Then, in the second stage, differential evolution based optimization method was implemented to discover the location and severity of the damage in the structure. Nobahari *et al*. 2017b presented a two-step method to precisely detect the location and severity of the damage in truss structures. In the first step, damage-suspected members were detected by an index based on residual force vector to decrease search space dimensions. In the second step, genetic algorithm and Efficient Correlation Based Index (ECBI) as its objective function in which the first few frequencies of the structure are considered in both damaged and healthy states, were employed to precisely find the location and severity of damage.

In this paper, a novel technique which could be categorized as a member of the family of vibration-based damage detection methods, is introduced to detect the damage of indeterminate truss structures. For this purpose, three steps including Damage-Suspected Element Identification step, Imminent Damaged Element Identification step, and finally, Damage Severity Detection step are considered, respectively. In the first step, damage-suspected elements are identified using a residual force vector-based index. In the second step, a specific technique is presented to identify imminent damage elements among the damage-suspected elements detected in the previous step. Ultimately, in the third step, the damage severity of each imminent damaged element is calculated using a new relation relating residual local nodal force vector to mode shape vector.

The rest of the article is structured as follows: in Section 2, the proposed approach is described in details. In Section 3, three numerical examples under different damage scenarios are studied to evaluate the efficiency and highly quick function of the proposed method. Finally, Section 4 gives conclusions, followed by references.

2. Proposed approach description

As mentioned earlier, the proposed method consists of three steps including Damage-Suspected Element Identification step, Imminent Damaged Element Identification step, and finally, Damage Severity Detection step. Before describing these steps for a truss structure in details in the section, MRFV is presented for the different modes of the truss structure.

In order to formulate MRFV for the ith mode, consider the eigenvalue equation of the healthy structure as follows:

$$(\boldsymbol{K}_h - \omega_{hi}^2 \boldsymbol{M})\boldsymbol{\phi}_{hi} = \boldsymbol{0} \tag{1}$$

where $\boldsymbol{K}_h$ and $\boldsymbol{M}$ are the reduced stiffness and mass matrices of the healthy structure respectively; $\boldsymbol{\phi}_{hi}$ and ω_{hi} are the ith reduced mode shape vector and natural frequency of the healthy structure, respectively. Although mode shape vectors are dimensionless, in this study, their unit is considered length unit.

The reduced stiffness and mass matrices of a structure are respectively constructed from its total stiffness and mass matrices by removing the rows and columns corresponding to the degrees of the freedom (DOFs) of its supports.

When damage occurs in a structure, it may vary both the stiffness matrix and the mass matrix of the structure. As a result of these changes, damage causes both the natural frequencies and the mode shapes of the structure to be changed. In this study, it is assumed that damage only changes the stiffness matrix of the structure, so, the eigenvalue equation for the damaged structure can be written as follows:

$$(\boldsymbol{K}_d - \omega_{di}^2 \boldsymbol{M})\boldsymbol{\phi}_{di} = \boldsymbol{0} \tag{2}$$

where $\boldsymbol{K}_d$ is the reduced stiffness matrix of the damaged structure; $\boldsymbol{\phi}_{di}$ and ω_{di} are the ith reduced mode shape vector and natural frequency of the damaged structure, respectively.

Mares and Surace 1996 represented the reduced stiffness matrix of the damaged structure $(\boldsymbol{K}_d)$ as follows:

$$\boldsymbol{K}_d = \sum_{j=1}^{NE} (1-\alpha_j)\boldsymbol{k}_{hj}^e = \boldsymbol{K}_h - \sum_{j=1}^{NE} \alpha_j \boldsymbol{k}_{hj}^e \tag{3}$$

where $\boldsymbol{k}_{hj}^e$ is the expanded global stiffness matrix of the jth element of the total elements (*NE)* of the healthy structure and α_j is a reduction factor for reducing the stiffness of the jth element. α parameter values fall in the range [0 1]. The value of zero for an element indicates that the element is healthy while the value of unity represents that it is fully damaged.

By substituting Eq. (3) in Eq. (2), Mares and Surace 1996 provided the following expression for the ith MRFV of the structure.

$$\boldsymbol{R}_i = (\boldsymbol{K}_h - \omega_{di}^2 \boldsymbol{M})\boldsymbol{\phi}_{di} = \sum_{j=1}^{NE} \alpha_j \boldsymbol{k}_{hj}^e \boldsymbol{\phi}_{di} \tag{4}$$

$\boldsymbol{R}_i$ vector representing the ith MRFV, will undoubtedly have non-zero components corresponding to only those DOFs associated with damaged elements.

Now, it is possible to describe the steps of the proposed method for an indeterminate truss structure, respectively.

Step 1: Damage-Suspected Element Identification step (DSEI):

In this step, the Residual Force Vector Based Index (RFVBI) corresponding to the ith mode, proposed by Nobahari *et al*. 2017b, is used to identify the damage-suspected elements of the truss structure. The index formula is as follows:

$$\begin{aligned} &RFVBI_j \\ &= abs\left(\boldsymbol{T}_j(1,1{:}Dim)\right)\left(abs\left(\boldsymbol{R}_i\left(\boldsymbol{V}_j^{DOFs}(1{:}Dim)\right)\right).\right. \\ &\left.* \, abs\left(\boldsymbol{R}_i\left(\boldsymbol{V}_j^{DOFs}(Dim+1{:}2\times Dim)\right)\right)\right) \end{aligned} \tag{5}$$

where the symbols abs and ".*" denote absolute value and element-by-element multiplication, respectively. $\boldsymbol{T}_j$ is the transformation matrix of the j th structural element. $\boldsymbol{V}_j^{DOFs}$ is a vector containing the DOFs associated with the first and second nodes of the jth structural element. *Dim* is a parameter whose value is 2 for 2D trusses and 3 for 3D trusses.

After calculating RFVBI for all the elements of the structure, those elements with none-zero RFVBI are considered as damage-suspected elements.

Step 2: Imminent Damaged Element Identification step (IDEI):

In the step, imminent damaged elements are identified among the damage-suspected elements detected in step 1. For this purpose, Eq. (4) is needed to extend as shown below to get a relation between $\boldsymbol{R}_i$ and $\boldsymbol{r}_{ij}^l$,

$$\begin{aligned}\boldsymbol{R}_i &= \sum_{j=1}^{NE} \alpha_j \boldsymbol{k}_{hj}^e \boldsymbol{\phi}_{di} = \sum_{j=1}^{NE} \left(\boldsymbol{T}_j' \alpha_j \boldsymbol{k}_{hj}^l \boldsymbol{T}_j\right)^e \boldsymbol{\phi}_{di} \\ &= \sum_{j=1}^{NE} \left(\boldsymbol{T}_j' \alpha_j \boldsymbol{k}_{hj}^l \boldsymbol{T}_j \boldsymbol{\phi}_{di}^{\boldsymbol{t}} (\boldsymbol{V}_j^{DOFs})\right)^e \\ &= \sum_{j=1}^{NE} \left(\boldsymbol{T}_j' \boldsymbol{r}_{ij}^l\right)^e\end{aligned} \tag{6}$$

where

$$\boldsymbol{r}_{ij}^l = \alpha_j \boldsymbol{k}_{hj}^l \boldsymbol{T}_j \boldsymbol{\phi}_{di}^{\boldsymbol{t}} (\boldsymbol{V}_j^{DOFs}) \tag{7}$$

$\boldsymbol{k}_{hj}^l$ and $\boldsymbol{r}_{ij}^l$ are the local stiffness matrix and ith modal residual local nodal force vector of the jth element of the healthy structure, respectively. $\boldsymbol{\phi}_{di}^{\boldsymbol{t}}$ is the ith total mode shape vector of the damaged structure.

Now, to find imminent damaged elements among damage-suspected elements, it is enough to calculate $\boldsymbol{r}_{ij}^l$ from Eq. (6) for all the damaged-suspected elements to become rigid in comparison with other elements by multiplying their cross sectional area by a big number and then follow the following instruction.

The jth damage-suspected element will be an imminent damaged element if and only if the magnitude of $\boldsymbol{r}_{ij}^l$ is bigger than zero $\left(|\boldsymbol{r}_{ij}^l| > 0\right)$, else it will be an undamaged element.

Step 3: Damage Severity Detection step (DSD):

This step to be the last step, detects the damage severities of the imminent damaged elements identified in the previous step. To reach this purpose, it is sufficient to obtain α_j from Eq. (7) which could be categorized as a force-displacement relation, as follows:

$$\alpha_j = \frac{|\boldsymbol{r}_{ij}^l|}{|\boldsymbol{b}|}, \qquad j = 1,2,\dots,NIDE \tag{8}$$

where

$$\boldsymbol{b} = \boldsymbol{k}_{hj}^l \boldsymbol{T}_j \boldsymbol{\phi}_{di}^{\boldsymbol{t}} (\boldsymbol{V}_j^{DOFs}) \tag{9}$$

and NIDE is the Number of Imminent Damaged Elements.

Table 1 Different damage scenarios for the 25-bar planar truss structure

Scenario 1		Scenario 2	
Element No.	Damage Severity (%)	Element No.	Damage Severity (%)
8	20	3	20
22	15	7	25
25	25	20	25
		22	20

For better understanding of the proposed damage detection method, its flowchart is provided in Fig. 1.

3. Numerical examples

In this section, to show the highly swift performance of the proposed method for detecting the damage of indeterminate truss structures, three examples under different damage scenarios including a 25-bar planar truss, a 31-bar planar truss, and a 52-bar space truss are studied. The first modal parameters including the first natural frequencies and mode shape vectors of these problems, are only used for finding their damage scenarios. In these numerical examples, the damage is simulated as a relative reduction in the elasticity moduli of some specific members and the mass matrix is assumed to be lumped.

3.1 25-bar planar truss

The schematic topology and element numbers of the 25-bar planar truss are shown in Fig. 2. The truss has 25 elements, 12 nodes and therefore 24 degrees of freedom, 3 of which are restrained. All the elements are made of a material with a density of $7780\,kg\,/\,m\text{^}3$ and an elasticity modulus of $200\,GPa$. The cross-sectional area of each element is equal to $1\,cm^2$. The damage scenarios given in Table 1, are induced in the structure. Figs. 3 and 5 show the damage-suspected elements predicted by DSEI step for damage scenario 1 and 2, respectively. Figs. 4 and 6 portray the residual internal forces produced in damage-suspected elements and the first MRFV applied on the nodes of the structure for damage scenario 1 and 2, respectively.

According to Figs. 4 and 6, the imminent damaged elements for the different damage scenarios are the elements 8, 22, and 25 for damage scenario 1 and 3, 7, 20, and 22 for damage scenario 2 because only these elements have a none-zero residual internal force. Tables 2-3 provide the damage severities of the imminent damaged elements calculated using Eq. 8 for damage scenario 1 and 2, respectively. With comparing the information in these tables with those reported in Table 1, it could be easily understood that the calculated and induced damage severities are exactly equal in value for all imminent damaged elements. The reason for such prompt and precise obtained results could lean on the mathematical basis of the proposed technique. It performed solely one analysis to get to the solution and detect not only all damaged elements but also their individual damage severity precisely.

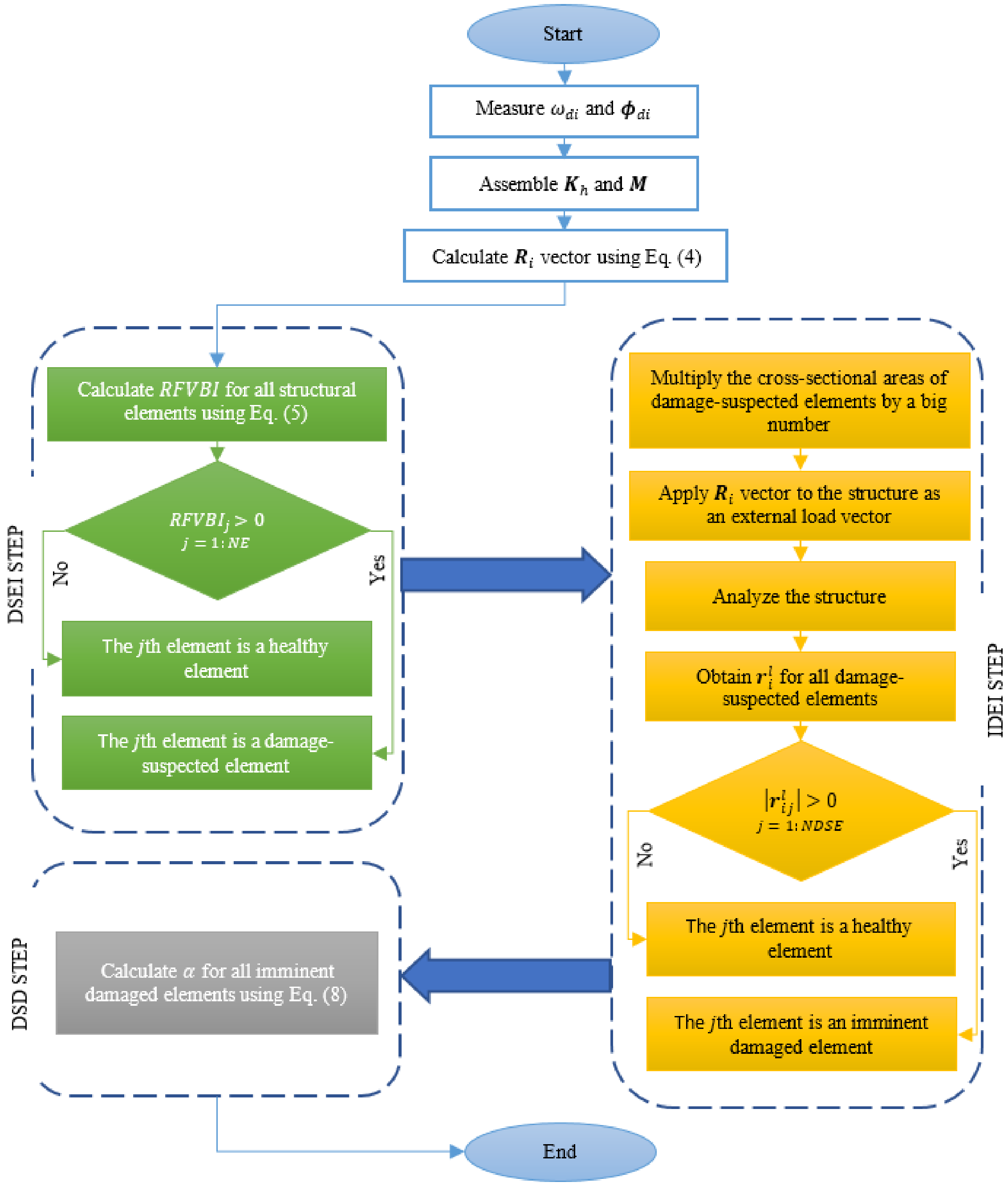


Fig. 1 Flowchart of the proposed damage detection method

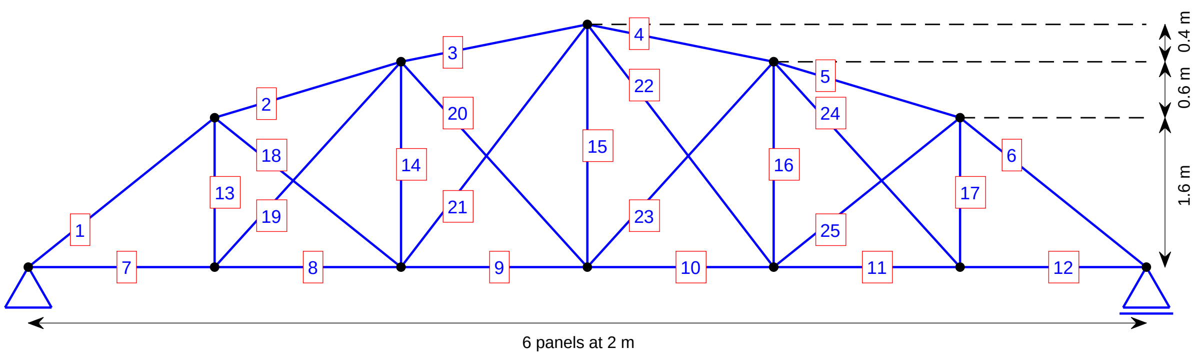


Fig. 2 The 25-bar planar truss structure

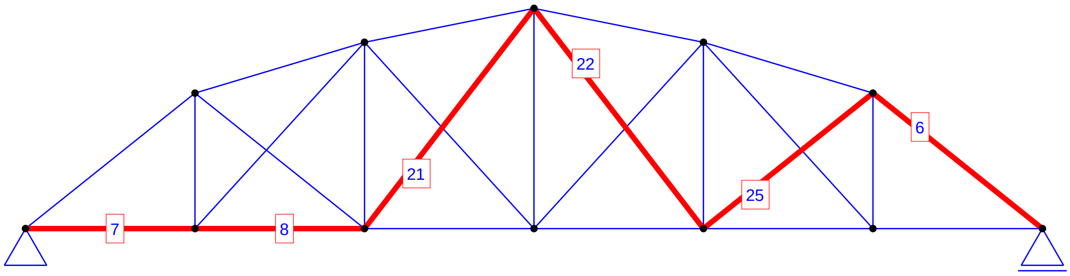
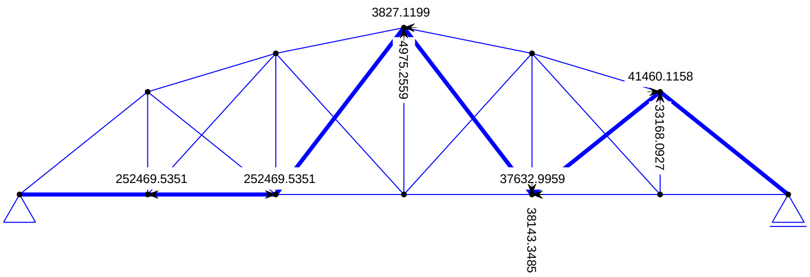
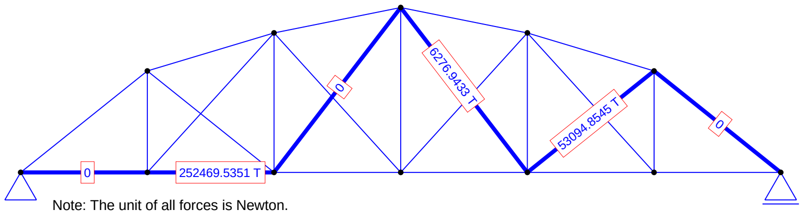


Fig. 3 Damage-suspected elements predicted for the 25-bar planar truss for damage scenario 1



(a) First MRFV



(b) Residual internal forces

Fig. 4 First MRFV and residual internal forces for the 25-bar planar truss for damage scenario 1

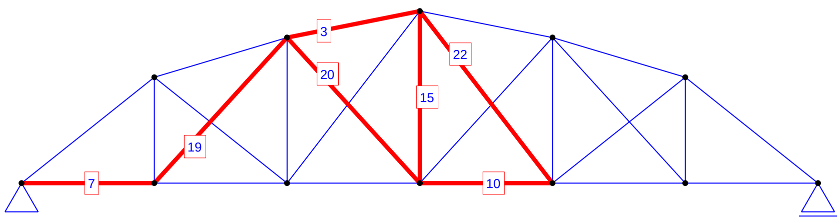


Fig. 5 Damage-suspected elements predicted for the 25-bar planar truss for damage scenario 2

Table 2 Damage severities of imminent damaged elements of the 25-bar planar truss for damage scenario 1

Imminent Damaged Element No.	$\lvert r_1^l \rvert$ (N)	$\lvert \boldsymbol{b} \rvert (N)$	$\alpha(\%)$
8	357045.8406	1785229.2031	20
22	8876.9384	59179.5894	15
25	75087.4634	300349.8535	25

Table 3 Damage severities of imminent damaged elements of the 25-bar planar truss for damage scenario 2

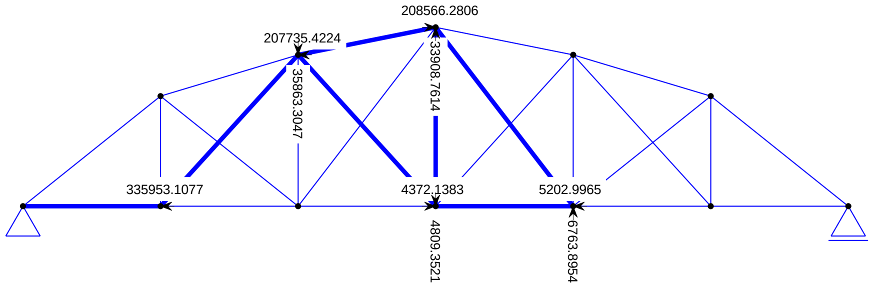
Imminent Damaged Element No.	$\lvert r_1^l \rvert$ (N)	$\lvert \boldsymbol{b} \rvert (N)$	$\alpha(\%)$
3	293294.6994	1466473.4968	20
7	475109.4412	1900437.7648	25
20	9191.8944	36767.5776	25
22	12068.2605	60341.3017	20

Table 4 Different damage scenarios for the 31-bar planar truss structure

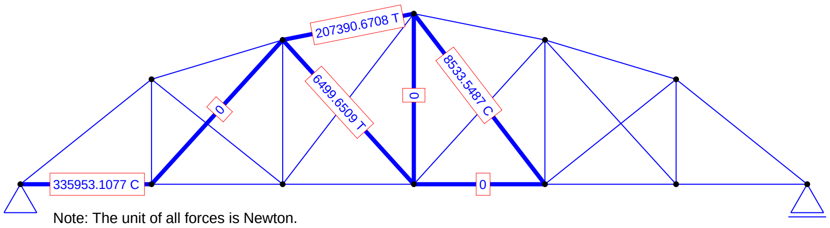
Scenario 1		Scenario 2	
Element No.	Damage severity (%)	Element No.	Damage severity (%)
1	30	6	8
2	20	8	13
		16	20
		22	16
		31	10

3.2 31-bar planar truss

The schematic topology and element numbers of the 31-bar planar truss are shown in Fig. 7. The truss has 31 members, 14 nodes and therefore 28 degrees of freedom, 3



(a) First MRFV



(b) Residual internal forces

Fig. 6 First MRFV and residual internal forces for the 25-bar planar truss for damage scenario 2

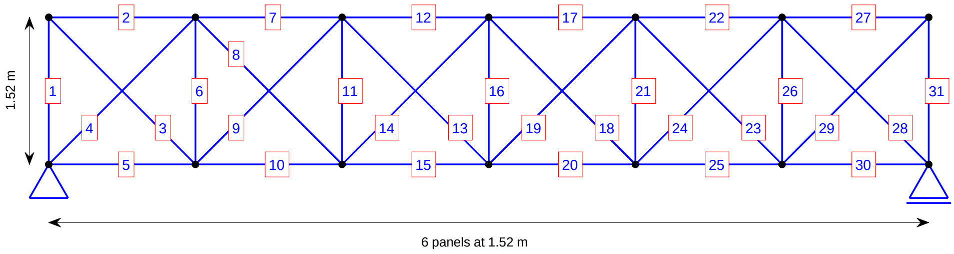


Fig. 7 The 31-bar planar truss structure

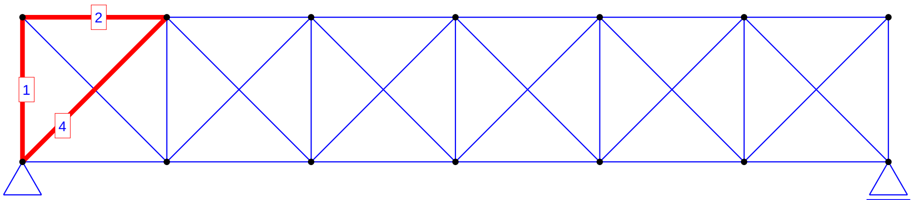


Fig. 8 Damage-suspected elements predicted for the 31-bar planar truss for damage scenario 1

Table 5 Damage severities of imminent damaged elements of the 31-bar planar truss for damage scenario 1

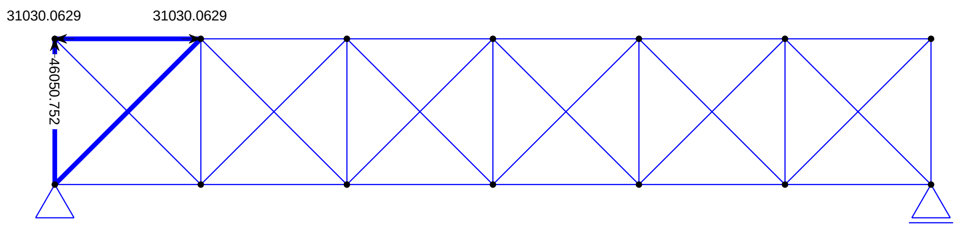
Element No	$\lvert r_1^l \rvert$ (N)	$\lvert \boldsymbol{b} \rvert (N)$	$\alpha(\%)$
1	65125.5981	217085.3270	30
2	43883.1358	219415.6791	20

of which are restrained. All the members are made of a material with a density of $2770\, kg\,/\,m^{\wedge}3$ and an elasticity modulus of $70\, GPa$. The cross-sectional area of each member is equal to $1\, cm^2$. The damage scenarios given in Table 4 are induced in the structure. Figs. 8 and 10 show the damage-suspected elements predicted by DSEI step for damage scenario 1 and 2, respectively. Figs. 9 and 11 portray the residual internal forces produced in damage-suspected elements and the first MRFV applied on the nodes of the structure for damage scenario 1 and 2, respectively.

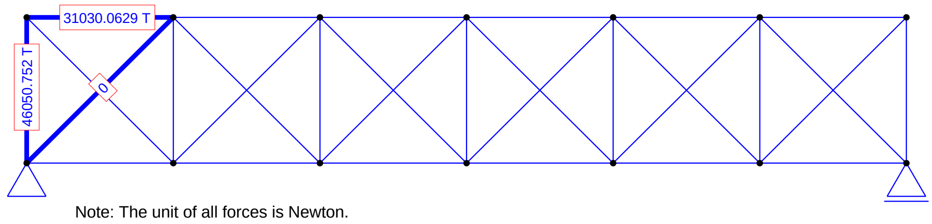
Table 6 Damage severities of imminent damaged elements of the 31-bar planar truss for damage scenario 2

Element No	$\lvert r_1^l \rvert$ (N)	$\lvert \boldsymbol{b} \rvert (N)$	$\alpha(\%)$
6	2359.1967	29489.9588	8
8	25327.6899	194828.3835	13
16	6789.6915	33948.4577	20
22	87859.8625	549124.1405	16
31	17475.8566	174758.5661	10

According to Figs. 9 and 11, the imminent damaged elements for the different damage scenarios are the elements 1 and 2 for damage scenario 1 and 6, 8, 16, 22, and 31 for damage scenario 2 because only these elements have a none-zero residual internal force. Tables 5-6 provide the damage severities of the imminent damaged elements calculated using Eq. 8 for damage scenario 1 and 2,



(a) First MRFV



(b) Residual internal forces

Fig. 9 First MRFV and residual internal forces for the 31-bar planar truss for damage scenario 1

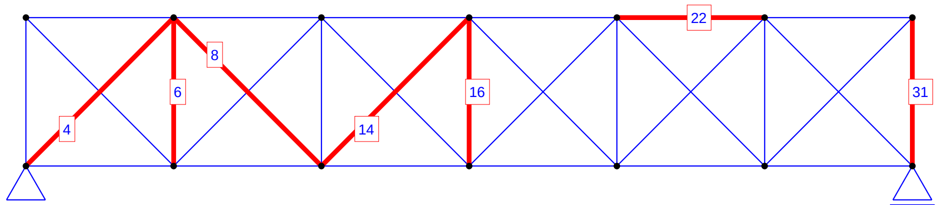
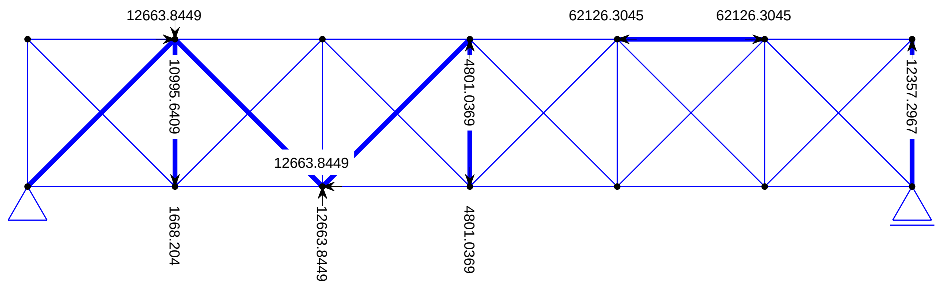
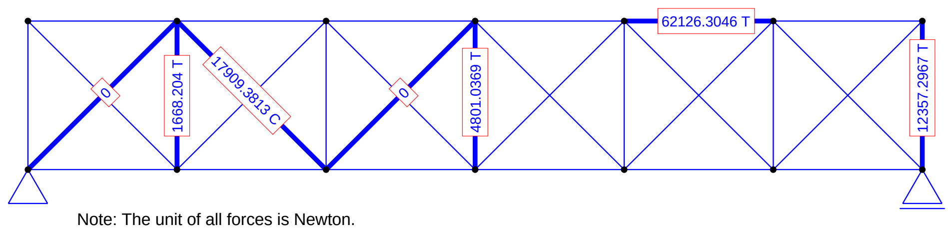


Fig. 10 Damage-suspected elements predicted for the 31-bar planar truss for damage scenario 2



(a) First MRFV



(b) Residual internal forces

Fig. 11 First MRFV and residual internal forces for the 31-bar planar truss for damage scenario 2

Table 7 Different damage scenarios for the 52-bar space truss structure

Scenario 1		Scenario 2	
Element No.	Damage severity (%)	Element No.	Damage severity (%)
8	25	5	10
33	15	6	35

respectively. With comparing the information in these tables with those reported in Table 4, it could be easily understood that the calculated and induced damage severities are exactly equal in value for all imminent damaged elements.

3.3 52-bar space truss

The two views of the schematic topology of the 52-bar space truss with element numbers are shown in Figs. 12-13.

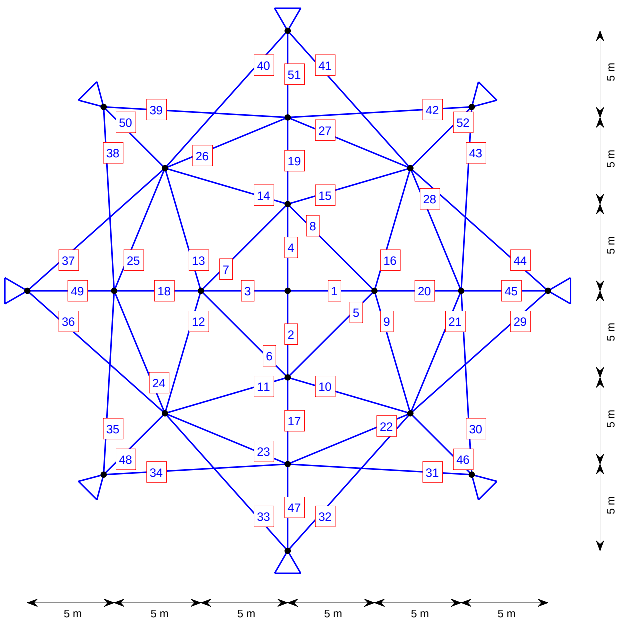


Fig. 12 Top view of the 52-bar space truss

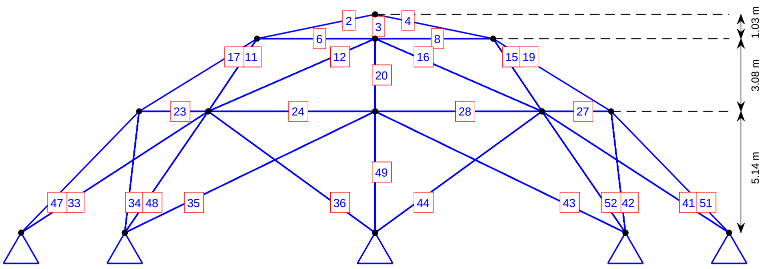


Fig. 13 Side view of the 52-bar space truss

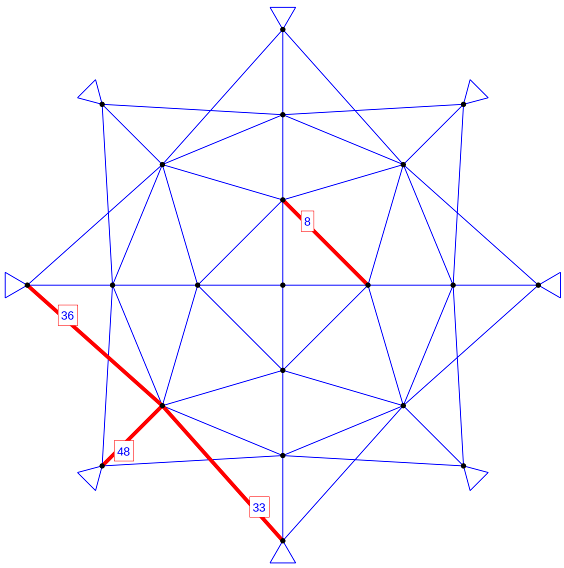


Fig. 14 Damage-suspected elements predicted for the 52-bar space truss for damage scenario 1

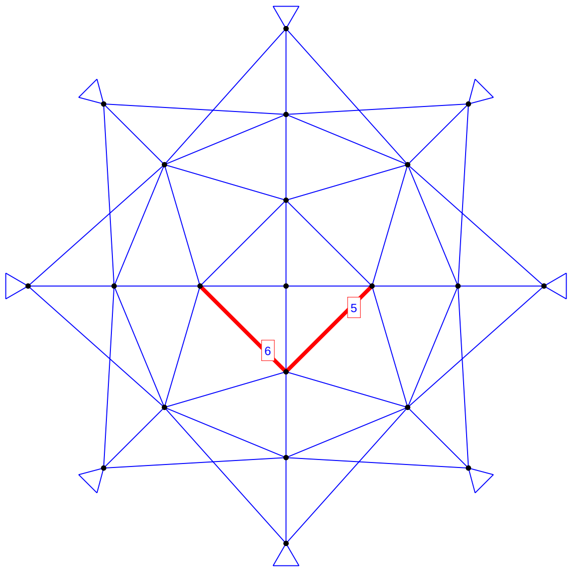


Fig. 15 Damage-suspected elements predicted for the 52-bar space truss for damage scenario 2

The truss has 52 elements, 21 nodes and therefore 63 degrees of freedom, 24 of which are restrained. All the elements are made of a material having a density of $7850\ kg\ /\ m$^3 and an elasticity modulus of 200 GPa. The cross-sectional area of each element is equal to $1\ cm^2$. The damage scenarios given in Table 7 are induced in the structure. Figs. 14-15 show the damage-suspected elements predicted by DSEI step for damage scenario 1 and 2, respectively.

The imminent damaged elements found by IDEI step for the different damage scenarios are the elements 8 and 33 for damage scenario 1 and 5 and 6 for damage scenario 2.

Table 8 Damage severities of imminent damaged elements of the 52-bar space truss for damage scenario 1

Imminent Damaged Element No.	$\|r_1^l\|$ (N)	$\|\boldsymbol{b}\|(N)$	$\alpha(\%)$
8	122354.1343	489416.5373	25
33	156159.6271	1041064.1810	15

Table 9 Damage severities of imminent damaged elements of the 52-bar space truss for damage scenario 2

Imminent Damaged Element No.	$\|r_1^l\|$ (N)	$\|\boldsymbol{b}\|(N)$	$\alpha(\%)$
5	45443.8010	454438.0105	10
6	394215.3537	1126329.5821	35

Tables 8-9 provide the damage severities of the imminent damaged elements calculated using Eq. 8 for damage scenario 1 and 2, respectively. With comparing the information of these tables with those reported in Table 7, it could be apparent that the calculated and induced damage severities are exactly equal in value for all imminent damaged elements.

4. Conclusions

In this paper, a three-step approach was proposed to detect the damage of indeterminate trusses. The need to only one structural analysis for detecting the damage of these structures was the main advantage of this method. In its first step, referred to as DSEI step, damage-suspected elements were predicted using an index based on residual force vector. In its second step, referred to as IDEI step, Imminent damaged elements were recognized among damage-suspected elements using a specific technique described in details in Section 2. Finally, in the last step, referred to as DSD step, the damage severity of each imminent damaged element was computed using a novel relation belonging to the group of force-displacement relations. Three numerical examples under different damage scenarios including two 2D trusses and one 3D truss, were studied to demonstrate the efficiency, simplicity and highly swift function of the proposed approach. In all the damage scenarios of these problems, the proposed method was able to accurately detect not only imminent damaged elements but also their individual damage severity. Accordingly, it may be noted that this method is innovatively capable of detecting the damage of indeterminate trusses. Although only used here for truss structures, it is clear from the precisely derived mathematical relations that this approach could be readily modified for other structures such as beams and frames.

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