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MODAL PARAMETER BASED DAMAGE LOCALIZATION IN STEEL BEAMS

LOKALIZACIJA OŠTEĆENJA U ČELIČNIM NOSAČIMA NA BAZI MODALNOG PARAMETRA

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- multiple damage
- damage detection
- damage localization
- mode shape curvature squares

Ključne reči
- čelični nosači
- višestruko oštećenje
- detekcija oštećenja
- lokalizacija oštećenja
- kvadrature modalnih oblika

Abstract

Structural health monitoring (SHM) is a technique used for evaluating the condition of a structure during its service life. Damage in a structure changes its geometric properties, which in turn affects its modal parameters and hence these modal parameters are helpful in damage detection. In this study, three steel beams, a plate beam, an I-section beam, and a channel section beam with boundary conditions as a cantilever and fixed at both ends are considered. Damage is simulated by reducing the element stiffness, and such damages are created at different locations in the beam resulting in single and multiple damage conditions. For the damage detection technique, modal parameters, such as frequency and mode shape for the first five modes have been extracted using a finite element (FE) analysis based software ANSYS. A frequency-based method is adopted for damage identification and damage localization is carried out by the Mode Shape Curvature Square (MSCS), a damage index formulated from mode shape. Moreover, the MSCS approach performed well in identifying multiple damages in the structure. The results obtained exemplify the optimum number of modes to be considered for locating multi-damage effectively in symmetrical and unsymmetrical section.

Izvod

Praćenje stanja konstrukcije (Structural Health Monitoring - SHM) je metoda za procenu stanja konstrukcije tokom radnog veka. Oštećenja u konstrukciji menjaju njene geometrijske karakteristike, što utiče na modalne parametre, a ovi parametri su potrebni u detekciji oštećenja. U radu se razmatraju: tri čelična nosača, nosač I profila, nosač C profila sa graničnim uslovima konzole i sa uklještenjem na oba kraja. Oštećenja se simuliraju redukovanjem krutosti elementa i takva oštećenja se formiraju na različitim mestima nosača, sa rezultujućim pojedinačnim i višestrukim oštećenjima. Primenom softvera ANSYS na bazi analize konačnim elementima (FE) u metodi detekcije oštećenja, utvrđeni su modalni parametri tipa frekvencije i modalnog oblika kod prvih pet modova. Za identifikaciju i lokalizaciju oštećenja, prihvaćena je metoda na bazi frekvencije sa primenom kvadratura modalnih oblika (MSCS), tj. indeks oštećenja formulisan preko modalnih oblika. MSCS pristup se pokazao dobrim u identifikaciji višestrukih oštećenja konstrukcije. Dobijeni rezultati pojašnjavaju optimalni broj modova, koje treba razmatrati pri efikasnom otkrivanju višestrukih oštećenja u simetričnom ili nesimetričnom preseku.

INTRODUCTION

Structural Health Monitoring (SHM) is the method of examining the condition of a structure which helps to maintain its integrity without leading to any manner of potential risks during its service life. The application of SHM made by Rytter /1/ leads to four stages of damage detection, which are: identification, localization, quantification and balance life of the structure. Several researchers have carried out their work in the field of damage detection. Agarwalla et al. /2/ presented a brief technique for the identification of damage using modal parameters. Nguyen /3/ discussed a study based on mode shape for damage identification. Jassim et al. /4/ carried out analytical and experimental studies on the effect of a crack in a cantilever circular steel beam and cracks in the beam were located with the help of natural frequency. Once damage in a structure is detected, it is necessary to locate it. Hou et al. /5/ proposed a method that increases the sensitivity of modal information towards a local damage by adding virtual masses to the structure. Khoshnoudian et al. /6/ presented a damage assessment method based on parameter estimation using the modal response for a truss and frame structure. Hence it is also possible to locate damage in the global structure. Damage location in a continuous beam is determined by Stubbs et al. /7/ using changes in modal data of the post-damaged beam. Next step of damage detection is quantification of damage. In research works /8-9/ the authors have used pre- and post damaged modal strain energy of the structure to quantify the damage. Damage in the structure results in perturbation of its physical properties, such as mass, stiffness, which leads to changes in the modal parameters. These parameters are used to formulate damage detection methods, such as the Frequency Based Damage Detection (FBDD) method, the Mode-Shape Based Damage Detection (MBDD) method, the Mode Shape Curvature Square (MSCS) method. Mohan et al. /10/ studied changes in experimental and analytical natural frequencies of an intact and damaged structure for damage assessment. A novel method is proposed by Choi et al. /11/ for calculating the natural frequencies of a multiple cracked beam and detecting unknown number of multiple cracks from measured natural frequencies. Wang et al. /12/ proposed a method based on natural frequency to identify the damage at the supports including the loose or missing fasteners, thus a shift in natural frequency indicates damage. Maia et al. /13/ performed analysis on a free-free beam to locate the damage with the aid of mode shape. Kim et al. /14/ illustrated that mode shape-based identification of damage achieved better results than frequency-based approaches. Hence, to locate damage in a structure, mode shapes are required. A damage index is derived by Rucevskis et al. /15/ based on mode shape curvature square (MSCS) for the localization of damage. MSCS is characterized as the difference of the damaged structure's curvature square and the intact structure's curvature square. This paper addresses the identification of damage by modal parameters in plate beam, I-section beam and channel section beam with different boundary conditions. The beams are damaged in such a manner that single and multiple damage cases are created, the beams are damaged at three locations in the multi-damage case. Most of the research work is performed on a symmetrical section only, but this study also focuses on the symmetrical and unsymmetrical section. The aim of conducting a study on the unsymmetrical section is to determine the number of modes required to locate the damage.

NUMERICAL MODELLING

In this study three steel beams are considered as shown in Fig. 1. Intact and damaged condition beams with single and multiple damage cases are studied.

Dimensions of the plate beam shown in Fig. 1a are length L = 1000 mm; width b = 100 mm; depth d = 10 mm. ISMB 100 is adopted as shown in Fig. 1b with depth d = 100 mm; flange width b_f = 75 mm; flange thickness t_f = 7.6 mm; web thickness t_w = 4 mm. ISMC 100 is considered as shown in Fig. 1c with dimensions as depth d = 100 mm; flange width b_f = 50 mm; flange thickness t_f = 7.5 mm; web thickness t_w = 4.7 mm. Structural steel has a density of ρ = 7850 kg/m^3. The finite element software ANSYS is used to model the beams and modal analysis is performed. SOLID 186 and SOLID187, which are 3-D 20 noded and 3-D 10 noded elements are used for the modelling. The equation of motion for the multi-degree of freedom (MDOF) system can be written in a matrix form as given in Eq.(1), neglecting the damping,

$$[\mathrm{M}]\{\ddot{X}(t)\}+[\mathrm{K}]\{X(t)\}=\{F(t)\}\,, \qquad (1)$$

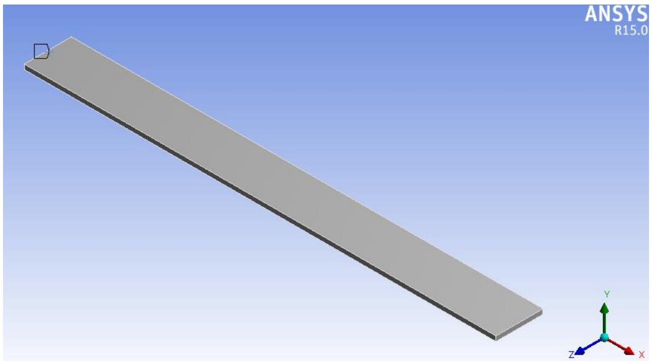
where: [M] and [K] are mass and stiffness matrix, respectively, of size (M×M); $\{X(t)\}$ is displacement vector; and $\{F(t)\}$ is applied force vector.

The eigenvalue problem of the system in i-th mode is expressed as in Eq.(2).

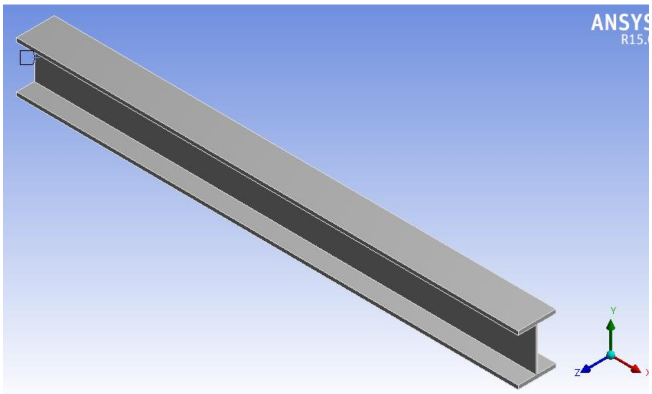
$$\left(-\omega_i^2[\mathrm{M}]+[\mathrm{K}]\right)\{\phi_i\}=\{0\}\,, \qquad (2)$$

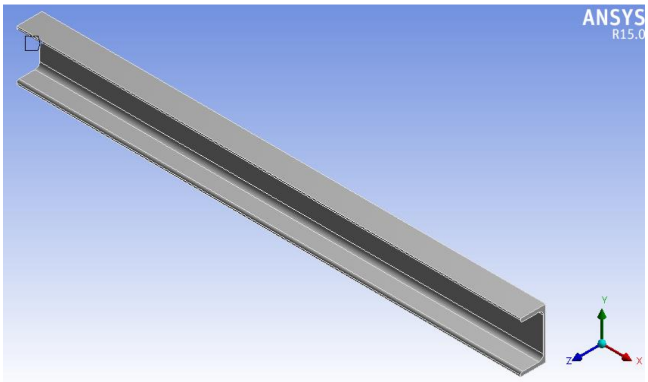
where: ω_i^2 and $\{\phi_i\}$ are eigenvalue and corresponding normalised eigenvector.

As mentioned in /17/, free vibration analysis provides suitable information for the detection of single and two damages.



a) plate beam


b) ISMB 100



c) ISMC 100

Figure 1. Steel beams for damage detection.

DAMAGE DETECTION TECHNIQUE

When a structure is damaged, it becomes more flexible at that location and causes a change in modal properties, i.e. decrease in natural frequency. But these changes are very small for damage detection in the structure. Mode shape curvature square (MSCS) based technique is adopted for the present problem. A flow chart presented in Fig. 2 explains the method adopted in this paper.

The mode shape curvature in Eq.(3) is computed from the central difference approximation method, where 'v' is mode shape and h is the distance between the nodes,

$$v_i''=\frac{v_{i+1}-2v_i+v_{i-1}}{h^2}\,. \qquad (3)$$

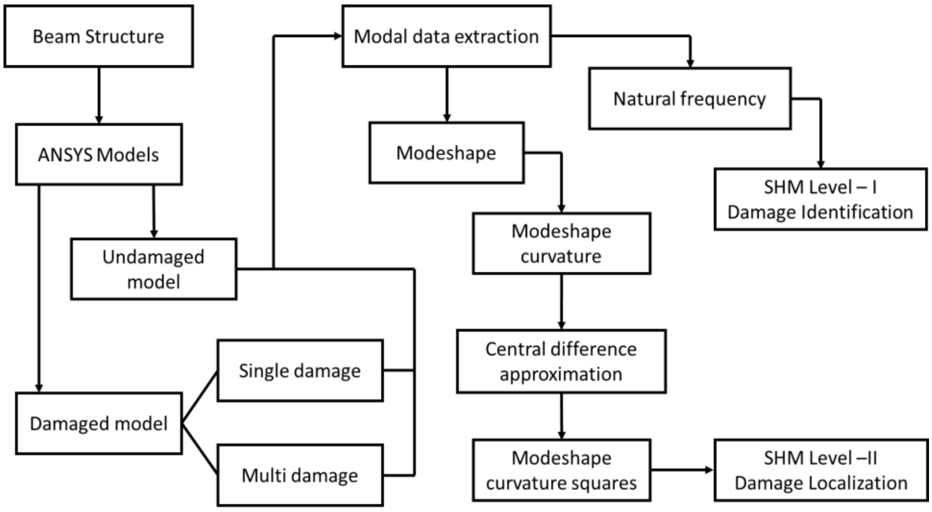


Figure 2. Damage detection strategy flowchart.

MSCS in Eq.(4) is the difference between the mode shape curvature squares of damage and intact structure,

$$(\Delta v_i'')^2 = \left|(v_i'')^{d2} - (v_i'')^2\right| , \tag{4}$$

where: $(v_i'')^2$ is for intact state; and $(v_i'')^{d2}$ for damaged state.

To avoid any loss of information, all modes considered shall be taken into account in the calculation and the damage index shall be formed as given in Eq.(5),

$$MSCS_i = \frac{1}{N}\sum_{n=1}^{N}(\Delta v_i'')_n^2 , \tag{5}$$

where: N - number of modes considered.

As the damaged structure has a greater amplitude than the intact structure, the MSCS will always be a positive value, consequently a distinctive peak will be shown at the damage location.

RESULTS AND DISCUSSION

After conducting the FE analysis of beams using ANSYS, modal parameters frequency and mode shape are extracted, which are crucial for damage detection. The effect of different boundary conditions and the number of modes to be considered for localization of damage are also discussed.

Single damage

The frequency of the plate beam is compared to the intact and damaged condition and D1, D2, and D3 indicate single damage at 250, 500 and 750 mm from the support. The change in frequency from intact state indicates the presence of damage.

Natural frequency variation for cantilever plate beam is shown in Table 1 and for the fixed plate beam is shown in Table 2 for the intact and damaged condition. A negative value indicates a decrease in modal frequency, while a positive value indicates an increase in modal frequency.

The MSCS method helps to locate both single and multiple damage cases in the beam, thus providing adequate information for the localization of damage.

Figure 3 shows cantilever plate beam damaged at 250 mm from the fixed support, and Fig. 4 represents the damage location obtained by MSCS. The graph is plotted against MSCS and damage location (*x/L*), where *x/L* is the ratio of damage location to the beam length. The peak in the graph indicates damage at 250 mm.

Table 1. Frequency changes of intact and damaged cantilever beam.

Mode no.	Intact (Hz)	Damaged			% change in frequency		
		D1 (Hz)	D2 (Hz)	D3 (Hz)	D1 (Hz)	D2 (Hz)	D3 (Hz)
1	8.556	8.5003	8.5429	8.5616	-0.65101	-0.15311	0.065451
2	53.595	53.599	53.25	53.435	0.007463	-0.64372	-0.29854
3	149.96	149.38	149.94	148.78	-0.38677	-0.01334	-0.78688
4	293.55	292.1	291.65	291.71	-0.49395	-0.64725	-0.62681
5	484.61	484.03	484.32	484.06	-0.11968	-0.05984	-0.11349

Table 2. Frequency changes of intact and damaged fixed beam.

Mode no.	Intact (Hz)	Damaged			% change in frequency		
		D1 (Hz)	D2 (Hz)	D3 (Hz)	D1 (Hz)	D2 (Hz)	D3 (Hz)
1	54.471	54.48	54.241	54.474	0.016523	-0.42224	0.005508
2	150.02	149.43	150	149.32	-0.39328	-0.01333	-0.4666
3	293.77	292.31	291.84	292.31	-0.49699	-0.65698	-0.49699
4	484.91	484.33	484.62	484.44	-0.11961	-0.0598	-0.09693
5	723.09	722.23	718.11	721.58	-0.11893	-0.68871	-0.20883

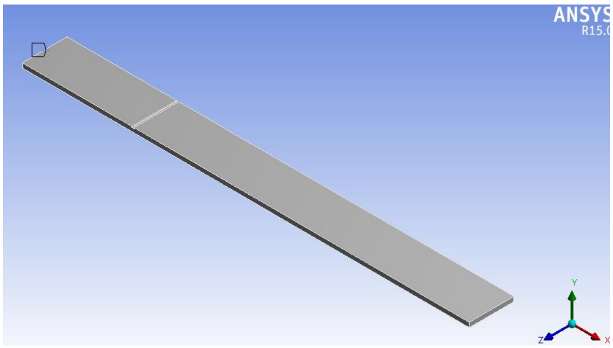


Figure 3. Damaged cantilever plate beam.

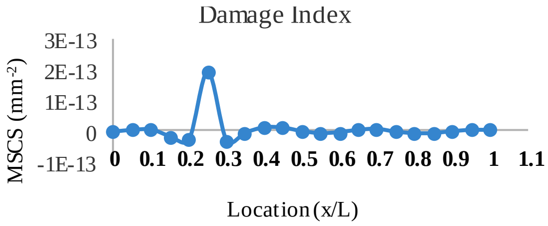


Figure 4. Localization of damage by MSCS.

Figure 5 shows the cantilever plate beam damaged at 500 mm from the fixed support, and Fig. 6 represents the damage location obtained by MSCS. The peak in the graph indicates damage at 500 mm.

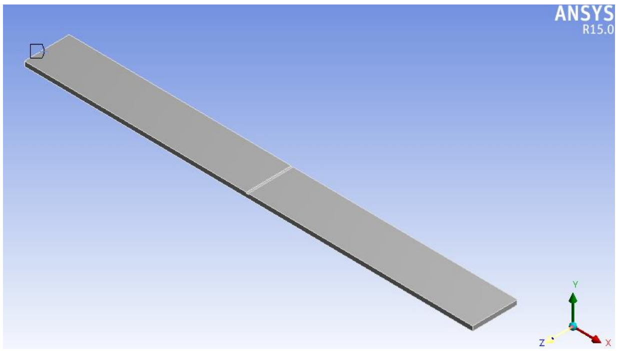


Figure 5. Damaged cantilever plate beam.

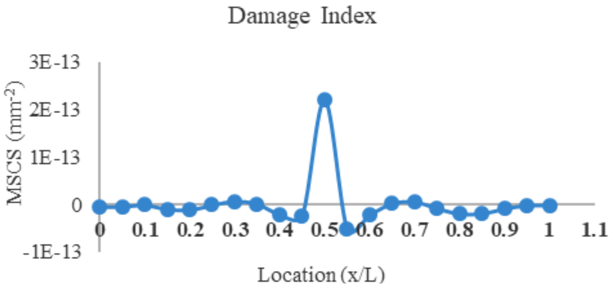


Figure 6. Localization of damage by MSCS.

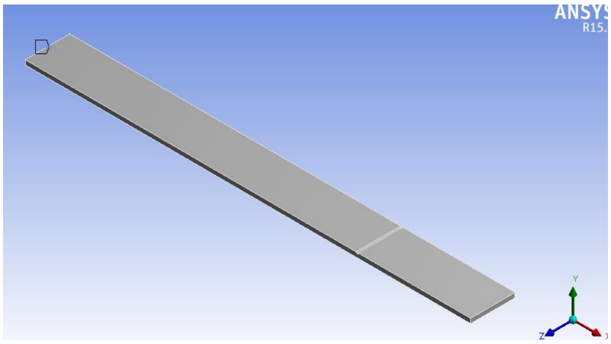


Figure 7. Damaged cantilever plate beam.

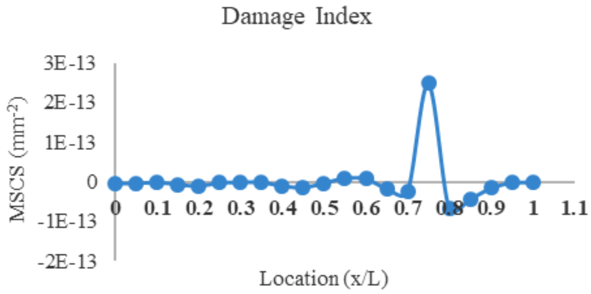


Figure 8. Localization of damage by MSCS.

Figure 7 shows the cantilever plate beam damaged at 750 mm from the fixed support, and Fig. 8 represents the damage location obtained by MSCS. The peak in the graph indicates damage at 750 mm.

Variation in natural frequency

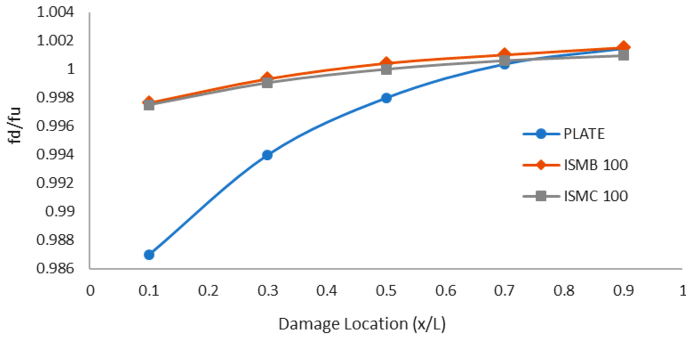


Figure 9. Frequency variation for different damage location.

To understand the variation in natural frequency with respect to the location of damage in the beam, a graph for the first modal frequency is plotted against frequency ratio (*fd/fu*) and damage location (*x/L*) for the three beams with boundary condition as a cantilever. Figure 9 shows a significant decrease in frequency as damage is located closer to the support. Since the plate beam has the most flexible section, any damage close to the support will make the beam even more flexible and will result in a very high reduction in stiffness. As the location of damage is away from the support, the decrease in natural frequency is less.

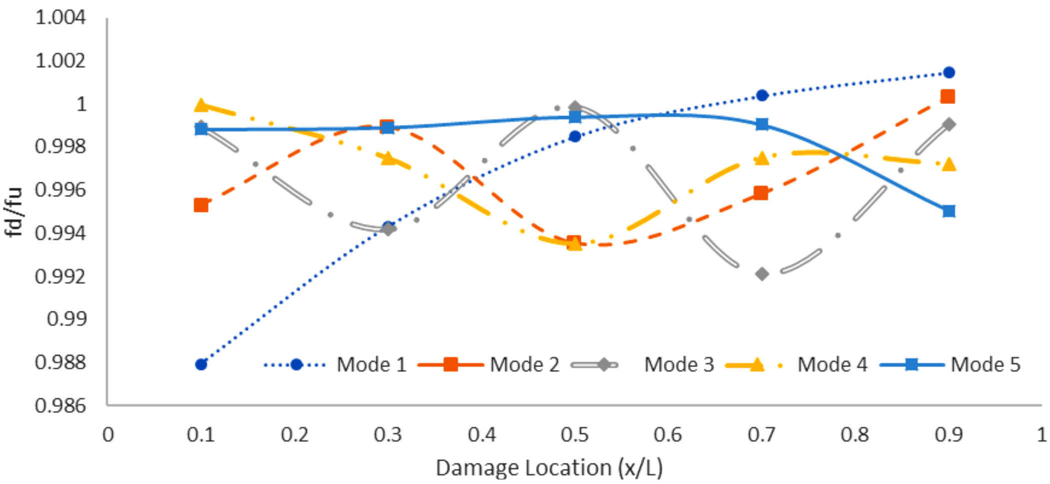


Figure 10. Frequency variation for different damage location including 5 modal frequencies.

To get a better understanding of the variation in natural frequency and location of damage, another graph is plotted, including the first five modal frequency of the plate beam. Figure 10 shows that damage located closer to the support can be identified clearly by the 1st modal frequency, but as the location of the damage is away from the support, the higher modal frequency identifies the damage.

Multiple damage

For intact and damaged conditions, the plate beam frequency is compared. Multiple damage is induced in the beam at 250, 500 and 750 mm from the support, respectively. The decrease of natural frequency from the intact state indicates the damage. A negative value represents a drop in modal frequency in Table 3, whereas a positive value suggests an increase in modal frequency.

Natural frequency variation for ISMB 100 is shown in Table 4 for intact and damaged conditions, and for ISMC 100 in Table 5 for the intact and damaged conditions.

Table 3. Modal frequency for plate beam.

Mode no.	Frequency (Hz)					
	Cantilever plate			Fixed plate		
	Intact	Damaged	% change	Intact	Damaged	% change
1	8.556	8.555	-0.01169	54.471	54.46	-0.02019
2	53.595	53.582	-0.02426	150.02	149.96	-0.03999
3	149.96	149.9	-0.04001	293.77	293.56	-0.07148
4	293.55	293.37	-0.06132	484.91	484.61	-0.06187
5	484.61	484.36	-0.05159	723.09	722.37	-0.09957

Table 4. Modal frequency for ISMB 100.

Mode no.	Frequency (Hz)					
	Cantilever ISMB 100			Fixed ISMB 100		
	Intact	Damaged	% change	Intact	Damaged	% change
1	119.28	119.16	-0.1006	562.27	563.68	0.250769
2	601.56	601.72	0.026598	1226.7	1229.7	0.244559
3	1323.9	1321.8	-0.15862	1996.4	2001.6	0.260469
4	1368.4	1369.9	0.109617	2647.7	2646.8	-0.03399
5	2189.1	2193.2	0.187292	2796.1	2805.6	0.339759

Table 5. Modal frequency for ISMC 100.

Mode no.	Frequency (Hz)					
	Cantilever ISMC 100			Fixed ISMC 100		
	Intact	Damaged	% change	Intact	Damaged	% change
1	115.05	114.89	-0.13907	591.35	591.65	0.050731
2	617.2	616.44	-0.12314	1344.5	1344.5	0
3	1324.3	1322.6	-0.12837	2232.9	2232.4	-0.02239
4	1461.4	1459.8	-0.10948	2649.8	2649	-0.03019
5	2411.3	2409	-0.09538	3176.1	3179	0.091307

Plate section

Figure 11 shows the cantilever plate beam damaged at 250, 500 and 750 mm from the fixed end, and Fig. 12 shows location of damage obtained by MSCS method. The peaks in the graph show damage location at 250, 500, and 750 mm. This ensures that the MSCS method can be utilised to detect multiple damage locations.

Figure 13 shows damage located at 250, 500 and 750 mm in plate beam for fixed-fixed boundary condition, and Fig, 14 shows the peaks in the graph for damage localization using MSCS method. Results from the graph can be interpreted as damage can be located by MSCS method regardless of boundary conditions.

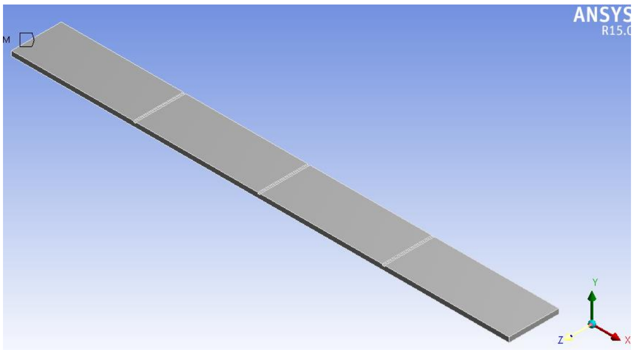


Figure 11. Damaged cantilever plate beam.

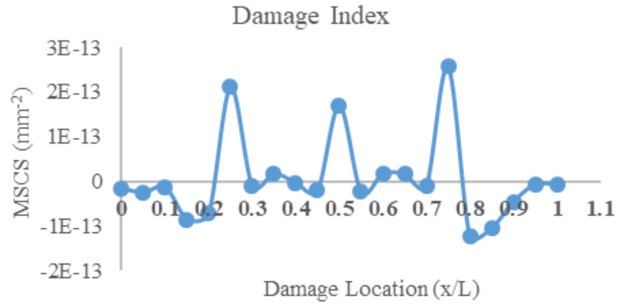


Figure 12. Localization of damage by MSCS.

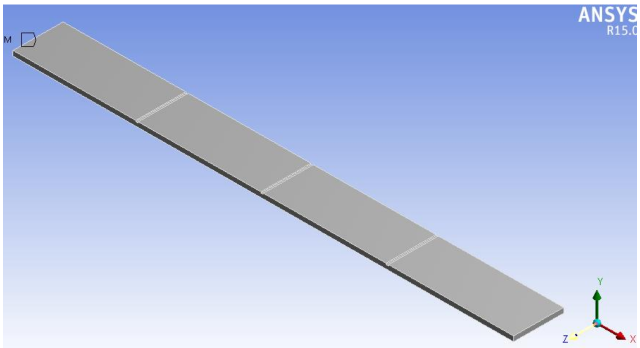


Figure 13. Damaged cantilever plate beam.

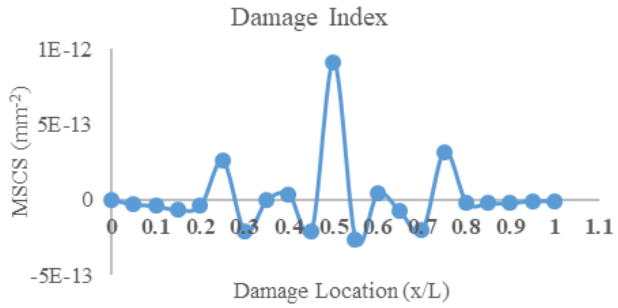


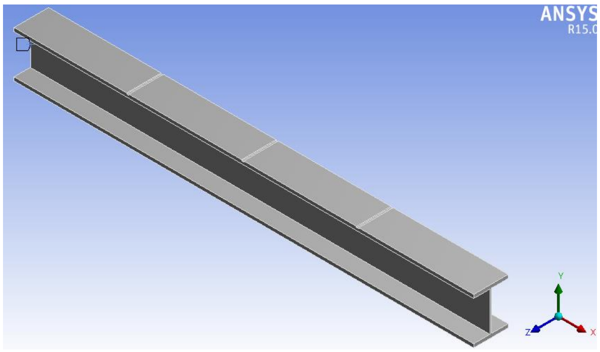
Figure 14. Localization of damage by MSCS.

ISMB 100

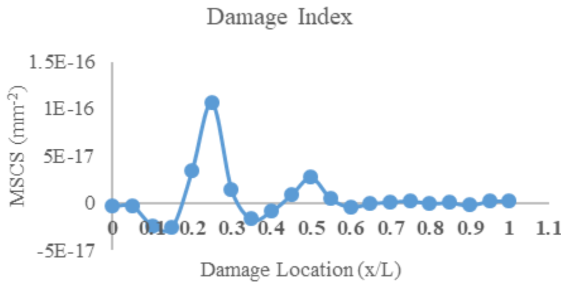
Damage detection with MSCS method is employed for I-section beam with cantilever and fixed boundary conditions. The first five modes are considered for locating the damage and results are shown in Fig. 15 for cantilever and in Fig. 17 for the fixed boundary condition. It is found that the first five modes are adequate to locate multi-damage in the beam. Figure 15e comprises of first four modes only and illustrates proper location of damage in a cantilever beam and Fig. 17d which involves the first three modes only, shows the best localization of damages in a fixed beam.

ISMC 100

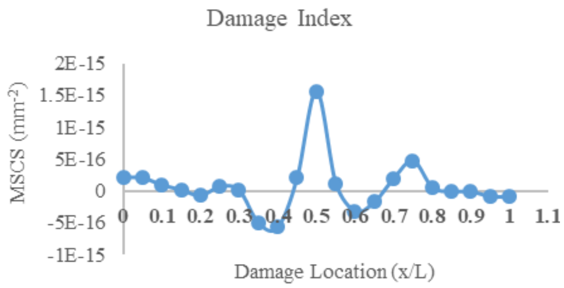
Damage detection with MSCS method is also demonstrated for the channel-section with cantilever and fixed boundary conditions. The first five modes are considered for locating the damage and results are shown in Fig. 16 for cantilever and in Fig. 18 for the fixed boundary condition. The first five modes are found to be sufficient to identify multi-damage in the beam. Figure 16e consists of the first four modes and indicates the better location of damage in a cantilever beam. Figure 18d containing the first three modes shows the accurate location of damage in the fixed beam. Figure 18e shows peaks other than the damage location due to the unsymmetry of the channel section which leads to the mixing of modes, i.e. the occurrence of torsional mode. For unsymmetrical sections, therefore, higher modes need to be avoided.



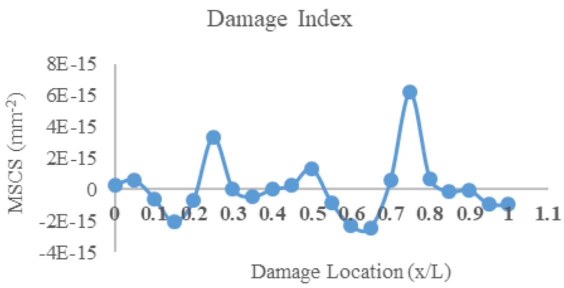
a) damaged cantilever ISMB 100



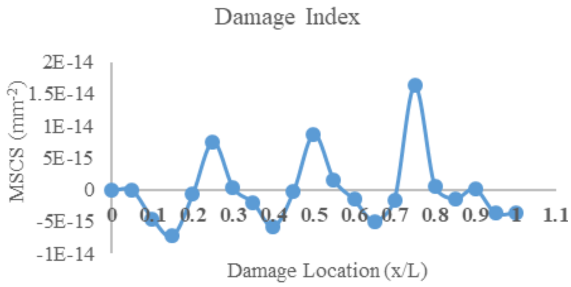
b) first mode



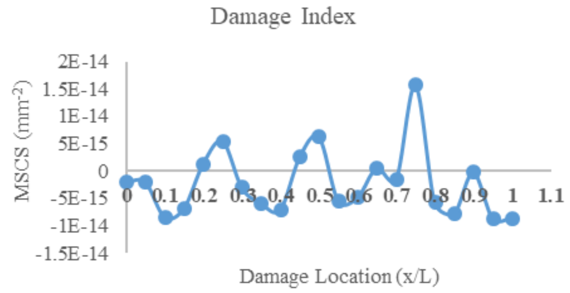
c) second mode



d) third mode

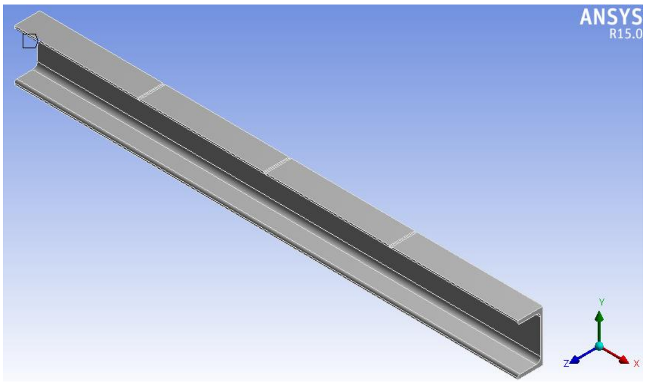


e) fourth mode

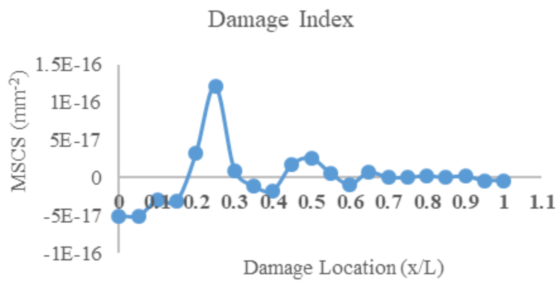


f) fifth mode

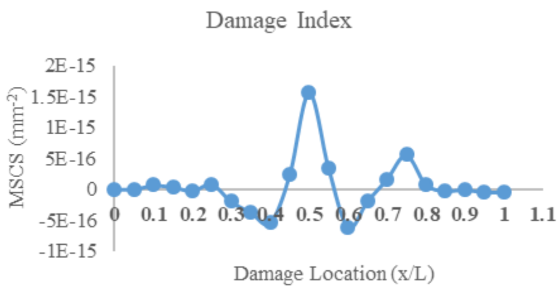
Figure 15. ISMB 100 with multiple damage and MSCS results.



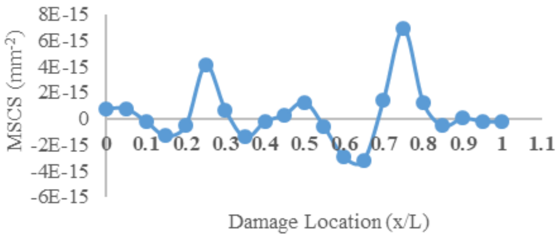
a) damaged cantilever ISMC 100



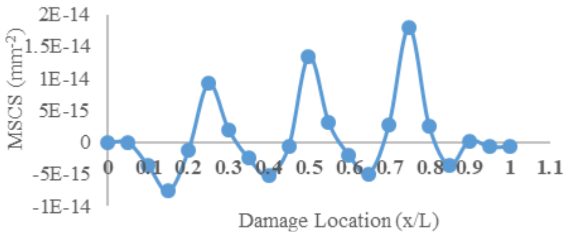
b) first mode



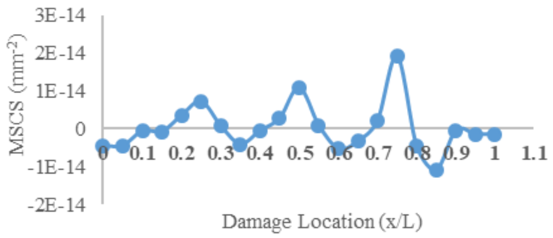
c) second mode



d) third mode

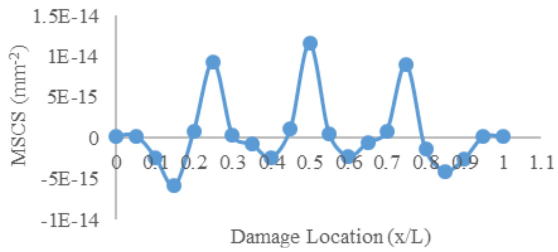


e) fourth mode

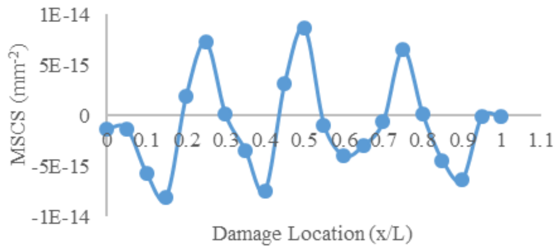


f) fifth mode

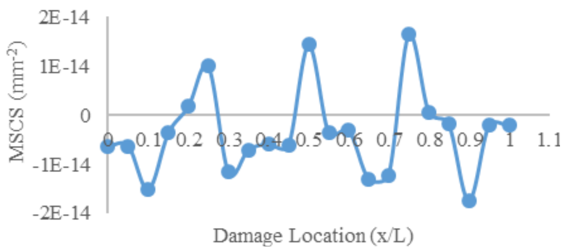
Figure 16. ISMC 100 with multiple damage and MSCS results.



d) third mode

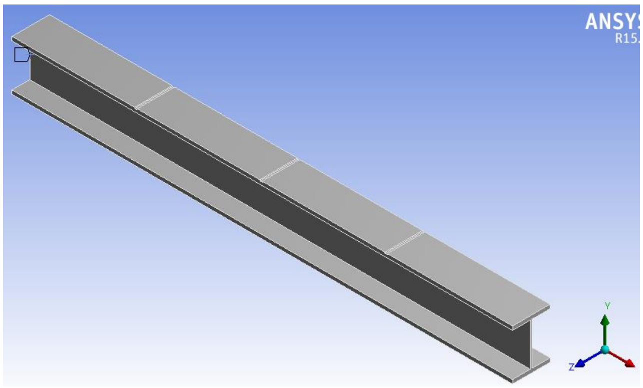


e) fourth mode

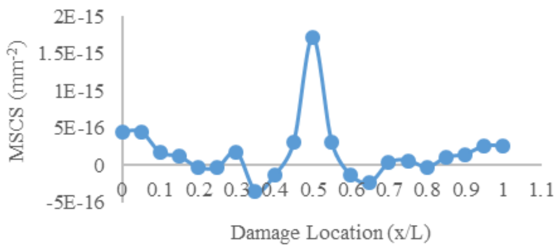


f) fifth mode

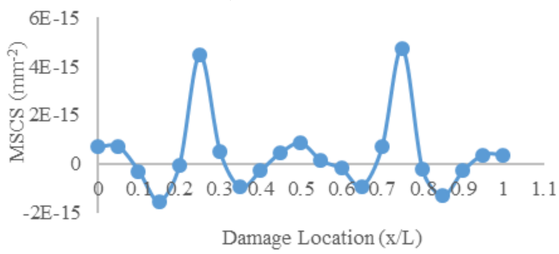
Figure 17. ISMB 100 with multiple damage and MSCS results.



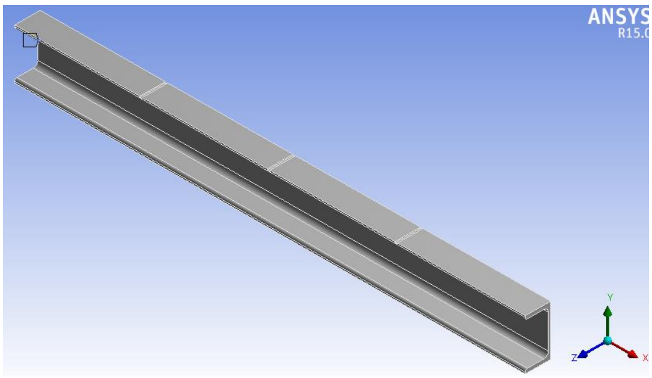
a) damaged fixed ISMB 100



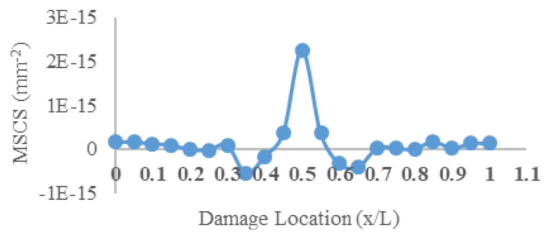
b) first mode



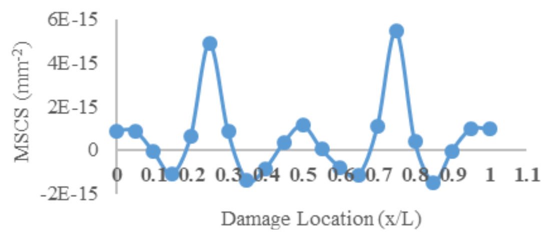
c) second mode



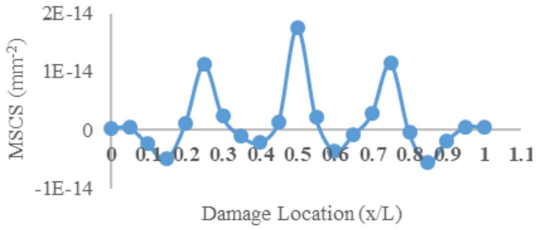
a) damaged fixed ISMC 100



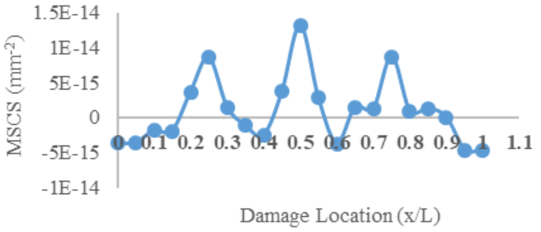
b) first mode



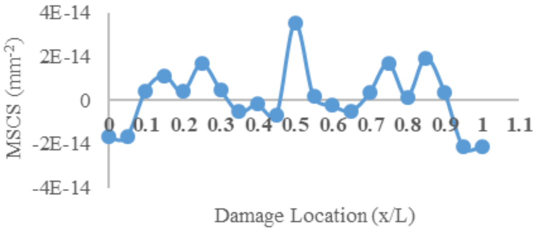
c) second mode



d) third mode



e) fourth mode



f) fifth mode

Figure 18. ISMC 100 with multiple damage and MSCS results.

CONCLUSION

This paper mainly emphasizes on the identification and location of damage in plate beam; I-section beam; channel-section beam, with the help of modal parameters. Damages studied in this paper are single and multiple damage cases with varying boundary conditions. Techniques adopted for damage detection are frequency-based method and mode shape curvature square (MSCS) method. For extracting modal data finite element analysis software ANSYS was used. The frequency-based method helps in determining the existence of damage, and the MSCS method for localization of damage in the three beams. From the above analysis results, the following conclusions can be made:

- in the cantilever beam, damage closer to the support is identified with 1 modal frequency ratio, whereas, damage away from the support is identified with the 5 modal frequency ratios,
- mode shape curvature square can locate single- as well as multiple damages in beams, regardless of the cross-section and boundary conditions,
- localization of damage is possible with the first 2 modes only, but it is recommended to include higher modes to minimize any loss of information,
- in the case of symmetrical sections, the accurate location of damage is detected by considering all the first five modes, whereas, for an unsymmetrical section, it is observed that higher number of modes are not able to find the proper location of damage due to mixing of the torsional into flexural modes. To avoid the problem of mixing in the higher modes, only the first 3 modes are taken for damage localization.

REFERENCES

1. Rytter, A., Vibration Based Inspection of Civil Engineering Structures, PhD Thesis, Aalborg University, 1993, Denmark.
2. Agarwalla, D.K., Parhi, D.R. (2013), *Effect of crack on modal parameters of a cantilever beam subjected to vibration*, Procedia Eng. 51(2013): 665-669. doi: 10.1016/j.proeng.2013.01.094
3. K.V. Nguyen (2014), *Mode shapes analysis of a cracked beam and its application for crack detection*, J Sound & Vibration, 333(3): 848-872. doi: 10.1016/j.jsv.2013.10.006
4. Jassim, Z.A., Ali, N.N., Mustapha, F., Abdul Jalil, N.A. (2013), *A review on the vibration analysis for a damage occurrence of a cantilever beam*, Eng. Failure Anal. 31: 442-461. doi: 10.1016/j.engfailanal.2013.02.016
5. Hou, J., An, Y., Wang, S., et al. (2018), *Structural damage localization and quantification based on additional virtual masses and Bayesian theory*, J Eng. Mech. 144(10): 1-9. doi: 10.1061/(ASCE)EM.1943-7889.0001523
6. Khoshnoudian, F., Esfandiari, A. (2011), *Structural damage diagnosis using modal data,* Scientia Iranica, 18(4):853-860. doi: 10.1016/j.scient.2011.07.012
7. Stubbs, N., Kim, J.-T. (1996), *Damage localization in structures without baseline modal parameters*, AIAAJ 34(8): 1644-1649. doi: 10.2514/3.13284
8. Shi, Z.Y., Law, S.S., Zhang, L.M. (2002), *Improved damage quantification from elemental modal strain energy change*, J Eng. Mech. 128(5): 521-529. doi: 10.1061/(ASCE)0733-9399(2002)128:5(521)
9. Entezami, A., Shariatmadar, H. (2014), *Damage detection in structural systems by improved sensitivity of modal strain energy and Tikhonov regularization method*, Int. J Dynam. Control 2: 509-520 (2014). doi: 10.1007/s40435-014-0071-z
10. Mohan, V., Parivallal, S., Kesavan, K. et al. (2014), *Studies on damage detection using frequency change correlation approach for health assessment*, Procedia Eng. 86(2014): 503-510. doi: 10.1016/j.proeng.2014.11.074
11. Nugyen, K., Khanh, L.T. (2014), *A novel method for crack detection in beam-like structures by measurements of natural frequencies*, J Sound Vibration, 333(18): 4084-4103. doi: 10.1016/j/jsv.2014.04.031
12. Wang, L., Zhang, Y., Lie, S.T. (2017), *Detection of damaged supports under railway track based on frequency shift*, J Sound & Vibration, 392: 142-153. doi: 10.1016/j.jsv.2016.11.018
13. Maia, N.M.M., Silva, J.M.M., Almas, E.A.M. et al. (2003), *Damage detection in structures: from mode shape to frequency response function methods*, Mech. Syst. Signal Process. 17(3): 489-498. doi: 10.1006/mssp.2002.1506
14. Kim, J.-T., Ryu, Y.-S., Cho, H.-M., Stubbs, N. (2003), *Damage identification in beam-type structures: frequency-based method vs mode-shape-based method*, Eng. Struct. 25: 57-67. doi: 10.1016/S0141-0296(02)00118-9
15. Rucevskis, S., Wesolowski, M. (2010), *Identification of damage in a beam structure by using mode shape curvature squares*, Shock and Vibration 17(2010): 601-610. doi: 10.3233/SAV-2010-0551
16. Orhan, S. (2007), *Analysis of free and forced vibration of a cracked cantilever beam*, NDT & E Int. 40(6): 443-450. doi: 10.1016/j.ndteint.2007.01.010