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Damage Assessment of Laterally Restrained Steel Beams Using Elemental Strain Energy

RushikeshGurpude[1] | Sanjay Denge[2]

[1]Department of Civil Engineering, V.M Institute of Engineering and Technology, Nagpur, Maharashtra, India
[2]Assistant Professor, Department of Civil Engineering, V.M Institute of Engineering and Technology, Nagpur, Maharashtra, India
Corresponding author Email ID: gurpuderishi@gmail.com

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ABSTRACT

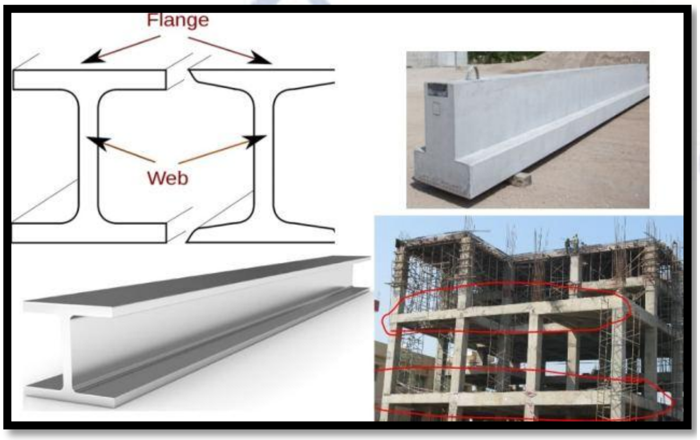
This paper presents the analytical investigation of laterally restrained built up steel beam under dynamic response using finite element software ABAQUS. The main objective of this study was to estimate the mode shapes and mode shape curvature of the laterally restrained built up steel beam. The three parameters such as modal frequencies, mode shapes and mode shape curvature are suggested for identifying the damages in built up steel beam. Damage assessment is done by linear perturbation free vibration study using finite element software ABAQUS. The frequency extraction methods for built up steel beam was done in ABAQUS to get the dynamic response. The Lanczos eigen solver was used for finding the mode shapes. Eigen value extraction, the natural frequencies and the corresponding mode shapes of a system were studied. Structural steel is used in load bearing frames in buildings , and as members in trusses, bridges, and space frames. It requires a fire resistance and corrosion protection. The main advantage of structural steel are strength, speed of erection, prefabrication and demountability. Damage accumulated in the structures due to its environmental loadings such as wind, snow, and ice. Structural Health Monitoring refers to the process of implementing damage detection and characterization strategy for engineering structures.

Keywords-ABAQUS, Laterally restrained steel beams, Strain Energy, Damage Assessment, Finite Element

1. INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Damage is defined as any internal change in a system that may prevent the system to perform the way it was intended to. It is undesirable and should be detected in its earlier stage itself to prevent catastrophic failure. Thus the process of identifying the presence of damage and its characterization are collectively known as damage assessment. Structural Health Monitoring (SHM) is the process of implementing a damage detection and characterization strategy for engineering structures, which is of most important concern now-a-days. Structural steel is used in load bearing frames in buildings, and as members in trusses, bridges, and space frames. It requires a fire resistance and corrosion protection. The main advantage of structural steel are strength, speed of erection, prefabrication and demountability. Damage accumulated in the structures due to its environmental loadings such as wind, snow, and ice. Structural Health Monitoring refers to the process of implementing damage detection and characterization strategy for engineering structures. Here damage is defined as the changes to the material and geometric properties of a structural systems, including changes to boundary conditions and system connectivity, which adversely affect the system performance. The process of implementing damage detection and characterization strategy for engineering structures is known as structural health monitoring. Here damage is defined as the changes to the material and geometric properties of a structural systems, including changes to boundary conditions and system connectivity, which adversely affect the system performance. Here, the dynamic response of the steel beam are identified by using finite element software. This research was to derive an innovative method to assess structural damage in steel truss bridges. First, it proposed a new damage indicator that relies on optimising the correlation between theoretical and measured modal strain energy. Second, in order to support the proposed damage indicator, the research studied the applications of two state of the art modal identifications techniques. Structural steel is used in load bearing frames in buildings, and as members in trusses, bridges, and space frames. It requires a fire resistance and corrosion protection. The main advantage of structural steel are strength, speed of erection, prefabrication and demountability. Damage accumulated in the structures due to its environmental loadings such as wind, snow, and ice.



[Fig.1.1: Types of beams in construction]

1.2 DAMAGE ASSESSMENT AND SHM

Damage assessment and structural health monitoring (SHM) based on measured vibration data is one of the most important issues related to the safety and reliability of engineering structures, especially in areas such as civil and aerospace engineering. Effective methods and tools developed for structural health monitoring and damage assessment can help not only to prevent hazardous events or catastrophic failures but also to prolong the service life of structures.

According to Rytter (1993), damage assessment involves four stages such as:

- level 1: Gives a qualitative indication that the damage might be present in the structure (detection),
- level 2: Gives estimate for the localisation of damage (localisation),
- level 3: Gives information about the amount of damage (assessment) and
- level 4: Gives information about the actual safety of the structure given a certain damage state (consequence).

The stages up to levels 3 of damage assessment in laterally restrained steel beams are discussed in this paper using multi criteria approach. When damage lies inside the structure and is not visible to the naked eye, it is possible to locate and quantify the damage using non-destructive tests and various analytical models such as Pai and Young (2001); Pai and Jin (1999); Wahab and Roeck (1999). Pandey et al. (1991) demonstrated mode shape curvature as a useful indicator in damage detection of beam structures. Doebling and Farrar (2001) tested changes in the natural frequencies and mode shapes of a bridge as a function of fault. Doebling et al. (1996) gave a comprehensive overview of the damage identification and health monitoring of structural and mechanical systems using changes in dynamic characteristics. Trisha et al. (2006) developed a method for damage detection and assessment in beams using the concepts of inverse method and fracture mechanics. C. Zang et al., (2007) studied the application of Global Shape Correlation (GSC) and Global Amplitude Correlation (GAC) criteria in structural health monitoring and damage detection. H.W. Shih et al., (2009) used the modal flexibility and the modal strain energy method, which are based on the vibration characteristics of the structure, in addition to changes in natural frequencies for damage assessment of beams and plates. Non-destructive evaluation methods are commonly used to find the damage in existing structures. Methods such as ultrasonic guided waves to measure the state of stress, or eddy current techniques to locate cracks can determine the exact location and extent of the damage. These methods are local health monitoring methods. Non-destructive evaluation (NDE) is often time consuming and expensive, and access is not always possible. Therefore, both global and local health monitoring is necessary.Structural dynamics is fundamentally concerned with the design, operation, and understanding of physical structures. A significant concern in the management of these, often very high-value, assets, is their state of health. When a structure sustains damage, this can have an extremely negative effect on its availability, and this will have serious implications for profitability and also the safety of any human operators or occupants. It is therefore important to implement some means of monitoring structural health so that incipient damage can be detected and remedial actions can be taken before negative consequences occur. The pertinent damage identification methodology for engineering structures is *Structural Health Monitoring* (SHM). This chapter presents an overview of SHM, with particular reference to implementations based on monitoring structural vibrations and waves. The main philosophy under discussion here is *data-based* SHM, where diagnostics are based on the interpretation of measured data directly, without recourse to physics-based models.

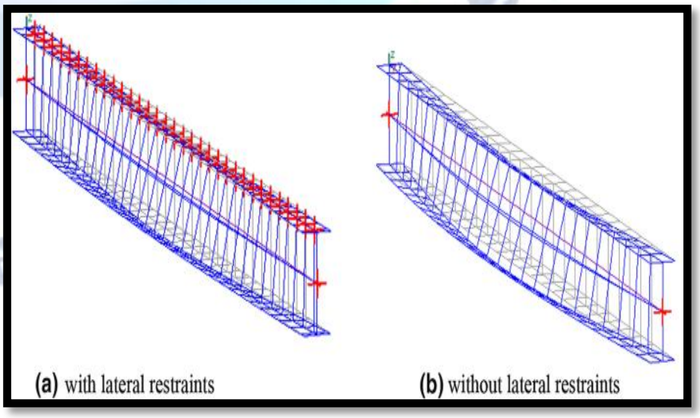
1.3 CONCEPT OF BUILT UP STEEL BEAM

An element of framed structures consisting of individual angle irons, channels, I-beams, and similar simple metal sections joined into a single unit by batten plates or lattices. Built-up beams are chiefly used as structural elements under compression, such as columns or chord members under compression in trusses. Built up steel beam is known as compound beam. A beam is made of structural units which are riveted, bolted, or welded together. When the span, load and corresponding to the bending moment are of such magnitudes that rolled steel beam section becomes inadequate to an provide required section modulus. The types of steel section are I-section, T-section, C- section and Angle section. Here, built up channel section has been used and it is generated by using finite element software – ABAQUS.

[Fig.1.2: Built Up Steel Beam]

1.4 CONCEPT OF LATERALLY RESTRAINED STEEL BEAMS

Laterally restrained steel beams consist of top flange of the beam restrained against lateral buckling in the plane of compression flange. Ideal lateral restraint helps bending of beam in the plane of load only. In the absence of lateral restraint, due to compressive stresses, the flange tends to buckle. At the same time, the tension flange tries to remain straight. This results in lateral torsional buckling. The capacity of the section in resisting bending thus reduces. To avoid this, full lateral support of the beam is essential. In many steel structures, especially in buildings, beams carry floor decks on top of them, and these floor decks provide restraint to the compression flange. In the absence of any such restraints, and in case the lateral buckling of beams is not accounted for in design, the designer has to provide adequate lateral supports to the compression flange. In this paper, fully laterally restrained pinned- pinned steel beam is considered for damage assessment study.



[Fig.1.3: a. beam with lateral restraints b. beam without lateral restraints]

1.5 AIM OF THE STUDY

Analytical investigation on the damage assessment of laterally restrained steel beams using elemental strain energy.

1.6 OBJECTIVES OF THE STUDY

- Damage assessment is done using linear perturbation free vibration study in ABAQUS, a Finite Element software, by introducing damage in the form of localised cross section reduction.
- Single and multiple damage conditions are analysed using dynamic response parameters such as modal frequencies, mode shapes and mode shape curvature.
- Treat the main loading bearing elements of structures, viz beam and plate, and complete bridge structures for damage assessment under different damage scenarios.
- Demonstrate the feasibility and capability of the proposed procedure through numerical examples.
- To study the working interface of ABAQUS Finite element software.

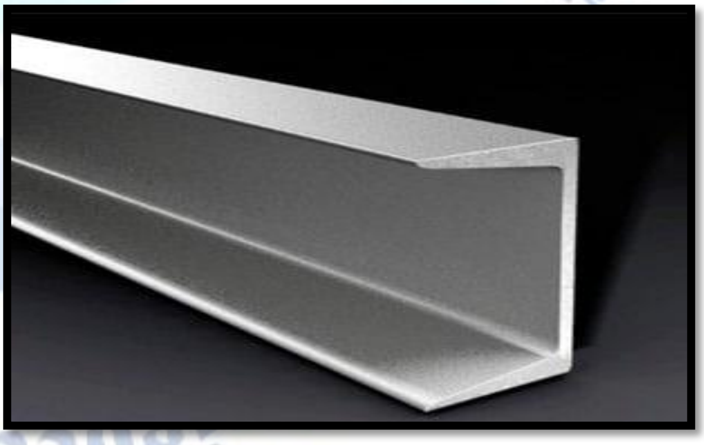
2. LITERATURE REVIEW

Sr. No	Paper Title	Findings
1	Damage Assessment of Laterally Restrained Steel Beams using Dynamic Response [ResmiG. and Baskar K.]	This paper uses the same correlation criterion for correlating the changes in displacement mode shapes of baseline and damaged beam, thereby quantifying the damage globally. A new correlation method is introduced for curvature mode shape, Curvature Assurance Criteria (CAC), to quantify the change of curvature mode shape curve from baseline undamaged one, to show the effect of all localised damages in the structure. MAC and CAC together provide an overall idea of total damage in the beam.
2	Behaviour of restrained steel beam at elevated temperature – parametric studies [Ahmed Allam and Ali Nadjai]	This paper aims to investigate computationally and analytically how different levels of restraint from surrounding structure, via catenary action in beams, affect the survival of steel framed structures in fire. This study focuses on examining the mid-span deflection and the tensile axial force of a non-composite heated steel beam at large deflection that is induced by the catenary action during exposure to fires.
3	Research on Laterally Restrained Built Up Steel Beam Under Dynamic Response [Sangeetha K, Vimala S]	This paper presents the analytical investigation of laterally restrained built up steel beam under dynamic response using finite element software ABAQUS. The main objective of this study was to estimate the mode shapes and mode shape curvature of the laterally restrained built up steel beam.

3. PROPOSED METHODOLOGY

3.1 PROCESSING OF DAMAGE ASSESSMENT PROCESS

- Model both baseline and damaged laterally restrained beams in FE software ABAQUS.
- Conduct a linear perturbation free vibration analysis in ABAQUS for built up steel beam to get the dynamic response.
- Extract modal parameters such as frequency and mode shape using Lanczos eigen solver of ABAQUS.
- Export the mode shape thus obtained to MS Excel to calculate the mode shape curvature.
- Identify the intensity of change in structural response using Modal Assurance Criteria (MAC) and Curvature Assurance Criteria (CAC).



[Fig.3.1: Channel Section]

3.2 VIBRATION ANALYSIS BY USING ABAQUS SOFTWARE

The frequency extraction procedure in ABAQUS is a linear perturbation procedure which performs eigen value extraction to calculate the natural frequencies and the corresponding mode shapes of a system. The Eigen value problem for the natural frequencies of an undamped finite element model is given by

$$(-\omega^2 M^{MN} + K^{MN})\, \Phi^{N} = 0$$

Where,

M^{MN} is the mass matrix

K^{MN} is the stiffness matrix

Φ^{N} is the eigenvector (the mode of vibration)

ω is the natural frequency (the mode of vibration)

M and N are degrees of freedom Abaqus/Standard

The Lanczos solver is the traditional architecture with the default eigenvalue extraction method because it has the most general capabilities. For the Lanczos method, the maximum frequency of interest or the number of eigenvalues has to be provided. Loads are ignored during frequency extraction analysis. The density of the material must be defined. Predefined fields cannot be prescribed during natural frequency extraction. Output variables such as stress, strain, and displacement which represent mode shapes are also available for each eigenvalue, these quantities are perturbation values and represent mode shapes.Modal Assurance Criteria (MAC) and Curvature Assurance Criteria (CAC) are the correlation indicators used to quantify the changes in dynamic response such as mode shape and curvature mode shape respectively of the built up steel beam. These are used to quantify the changes in structural response of the beam. The baseline and damaged laterally restrained steel beams are modelled in FE software ABAQUS, as a 3D conventional shell element with six degrees of freedom per node. The damage is provided in such a way to simulate corrosion by reducing the cross sectional area, the details of which are given in succeeding sections.

3.3 MODE SHAPE CURVATURE

Mode shape curvature, which is the double derivative of mode shape, is obtained by the following,

$$MC, \Phi''_{n,m} = \left(\frac{\Phi_{n+1,m} 2\Phi_{n,m} \Phi_{n-1,m}}{d^2}\right)$$

Where,

n = Number of node,

m = Number of mode,

d = Distance between two nodes,

Φ = Displacement mode shape

3.4 VERIFICATION OF ABAQUS MODEL

The ABAQUS model is verified by using the classical solution of free vibration of continuous system. The Euler Bernoulli's beam theory is one of the basic assumptions used in the differential equation of continuous system. The standard result of continuous system are derived for the beam. The fundamental frequency of a beam is obtained as

$$f = \frac{\Pi}{2L^2}\sqrt{\frac{EI}{A\rho}}$$

Where,

F-fundamental frequency,

L-Length of beam,

E-Young's Modulus of material,

I-Moment of Inertia,

A-Area of cross section and

ρ- Density of material. ISMC 350 section is considered with 2m length of beam, E=210x109 N/m^2,

I=10008x104 mm^4

A= 5366 x 104 m^2.

From equation, the fundamental frequency is obtained as 277.385 Hz.

4. ILLUSTRATIONS & RESULTS

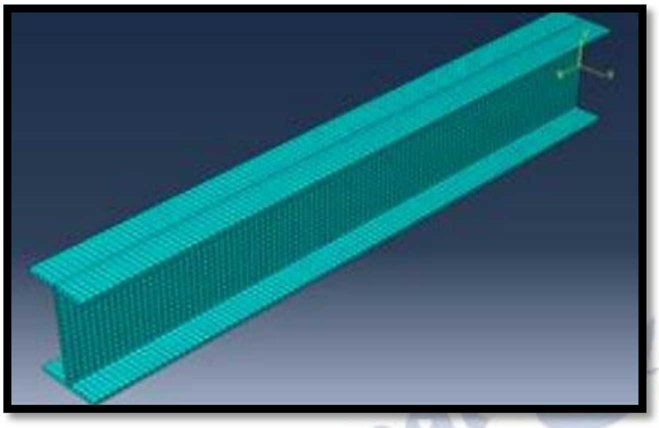
The damage is illustrated using a Finite Element modelling of built-up steel beam beam are done using ABAQUS 6.11. The built-up channel section is taken as ISMC 350, which is a standard built up section with 2m span, pinned-pinned end conditions, whose section properties are shown in Table 4.1. The material properties assigned are given in Table 4.2.

Table 4.1: Section properties of ISMC 350

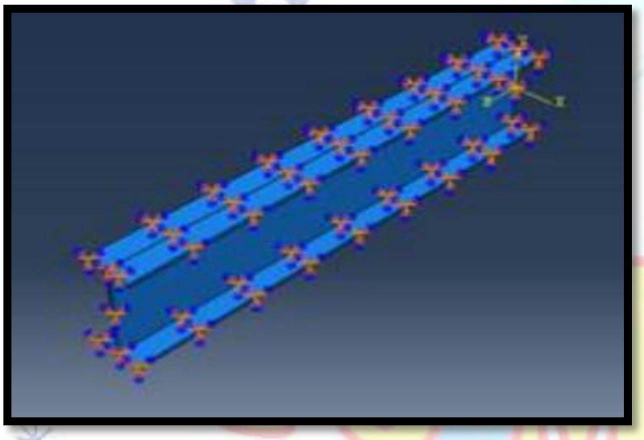
Thickness of flange	13.5 mm
Thickness of web	8.1 mm
Depth of C-section	350 mm
Width of flange	100 mm

Table 4.2: Material properties of beam

Poisons ratio	0.3
Modulus of elasticity	210x10^9 N/m^2
Density	7850 kg/m^3

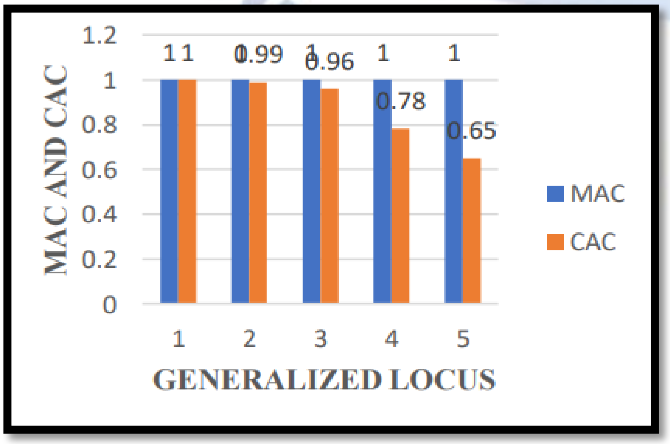


[Fig.4.1: Finite element mesh of steel beam]

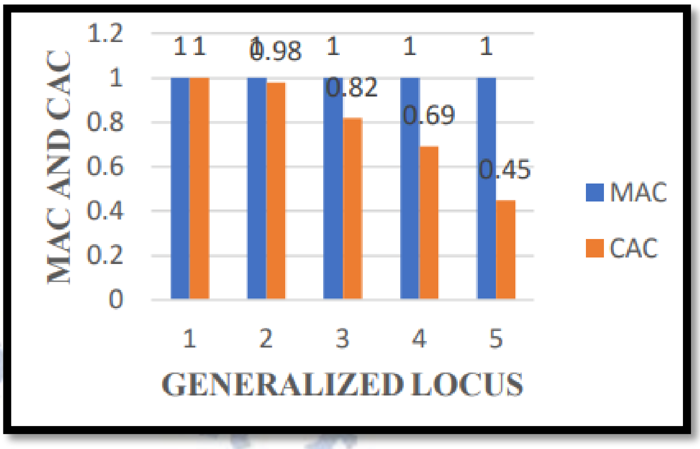


[Fig.4.2: Boundary condition of laterally restrained built up channel section beam]

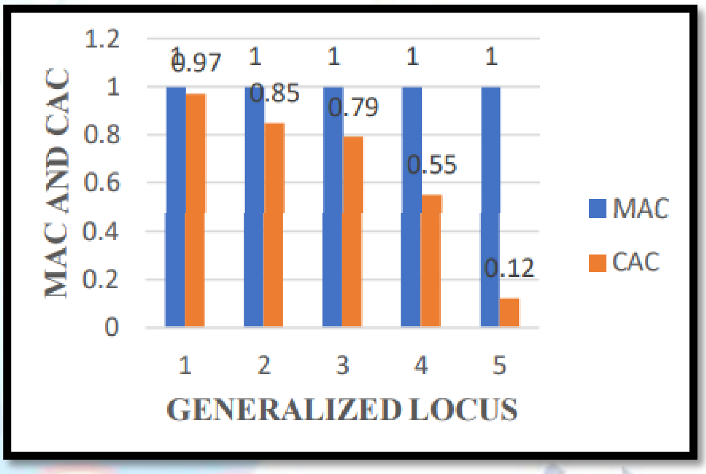
Thus, the mode shape and curvature mode shape can be used to identify the damage and locate the damage in laterally restrained built-up channel section beams. MAC and CAC are calculated using equations (3) and (4) for all cases of damages to quantify the change in the dynamic response such as mode shape and curvature mode shape are shown in fig 4.3(a), 4.3(b) and 4.3(c).



[Fig.4.3(a): MAC and CAC For AA1]



[Fig.4.3(b): MAC and CAC For AA2]



[Fig.4.3(c): MAC and CAC For AA3]

From the figures, it shows that the damaged induced is localised one. The MAC is found to be 1 for all causes of damages are described in this paper. The CAC values are varying with the respect to the cross section and location of damage in the beam. Here, the MAC and CAC are quantifying the changes in mode shape and curvature mode shape graphs with respect to corresponding baseline in terms of 0 and 1. Here, MAC values is near to and the CAC values is near to zero which indicate the presence of damage in the structure. Hence, the MAC and CAC will quantify the damages and the intensities of damages in the built-up steel beam.

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Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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