SM6 Fracture and Crack

Detection of edge crack modeled as rotational spring by using Bayesian filtering in beam like structure

Md Armanul Hodar[1], Eshwar Kuncham[2], Subhamoy Sen[3*]

[1] *M.Tech student, i4S Laboratory, Indian Institute of Technology Mandi, Mandi, India*
[2] *PhD student, i4S Laboratory, Indian Institute of Technology Mandi, Mandi, India*
[3] *Assistant Professor, i4S Laboratory, Indian Institute of Technology Mandi, Mandi, India*

[*] *Email: subhamoy@iitmandi.ac.in*

ABSTRACT

Numerical beam is an important structure type for replicating and idealizing several different real structures, e.g. bridges, high-rise structures etc. Towards development of damage detection approaches/ algorithms for bridge structure, present study has idealized it as a prismatic beam and an instance of localized structural damage is replicated as a through crack at the beam. The objective of this study is further to precisely localize the extent and location of such damages under severe ambient and model uncertainties. Particle filtering based structural health monitoring (SHM) approach has been employed in this study. Typical of such model-based algorithms, the real structural domain is discretized into finite elements with the damage attributed to any of these elements, rendering the localization precision being dependent on the discretization resolution. Current study modelled the damage as a independent massless rotational spring in the beam attributing the local stiffness deterioration of the real structure through the decay in the spring stiffness. To localize and quantify the real damage in the beam, the goal of present estimation approach is therefore set as to locate the position of such spring and further estimate its residual spring stiffness. This enables localization of the damage with a resolution much beyond the discretization density, and thereby helping the algorithm to be supported with much less compute-intensive models. The algorithm is validated for its sensitivity against noise and damage severity. The results demonstrate the algorithm to be efficient, prompt and precise in detecting damage in a structure.

Keywords: Particle filtering, Structural health monitoring, Beam like Structure, massless rotational spring ,finite element model, model-based algorithm

1. INTRODUCTION

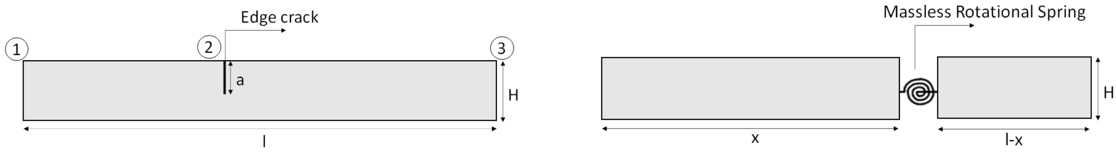
A crack/damage in an operational civil infrastructure is ideally supposed to be detected and isolated at the earlier possible time in order to avoid further progression of damage, economic loss and loss of precious human lives. With model assisted structural health monitoring (SHM) approach, the detection resolution, however, depends on model dimension and sensor density [Chasalevris and Papadopoulos(2006), Ghadami et al.(2013)Ghadami, Maghsoodi, and Mirdamadi]. Eventually, for high dimensional civil infrastructure, employment of high dimensional supporting model and dense instrumentation becomes imperative which might overshoot the cost of monitoring rendering the entire approach economically not viable. Present study proposes an innovative approach wherein high dimensional structures can still be estimated using cheaper computational models and sparse instrumentation with an objective to develop a practical SHM approach.

2. METHODOLOGY

Typical model-based SHM approaches defines the structural domain in terms of finite elements and damage is attributed in one of the elements. Eventually, finer is the discretization, the precise is the detection resolution, especially for localized damages, like cracks. In this study, such cracks are however modelled as massless rotational spring of infinitesimal length[Ghadami et al.(2013)Ghadami, Maghsoodi, and Mirdamadi, Lee(2009)]. The proposal is validated on beam structure of length (L) discretized into 'n' two-noded Euler Bernoulli beam (EBB) elements with the damage located in one of the elements. The damage element is further modelled as two EBB joined through a massless rotational spring. The reduction in rigidity (EI) and rotational stiffness (k_i) in actual beam of length l is thereby defined with the joint stiffness of the spring as defined in [Eur(2003)] in terms of stiffness reduction factor (γ),

$$k_i = \gamma \frac{EI}{l} \tag{1}$$

with γ varying within the range of $[0.5 - -25]$ (Pinned: $\gamma < 0.5$, flexible joint: $0.5 < \gamma < 8$, rigid joint: $\gamma >= 25$). With each 10% reduction in stiffness in actual beam, the corresponding change in γ is about 2.5. End fixity factor 'f_i' is further correlated to γ as $F_i = \gamma/(\gamma + 3)$ [Aswal et al.(2022)Aswal, Sen, and Mevel, Katkhuda et al.(2010)Katkhuda, Dwairi, and Shatarat].



(a) 3 nodded Beam element with edge crack

(b) Crack modelled as massless spring

Figure 1. Schematic diagram of modelled crack element of the beam

With a crack modelled as rotational spring (c.f figure 1), the Finite element approximation however changes with a modified mass and stiffness matrix (M_{cr} and K_{cr}) with their dependence on the end-fixity factor(F_i) (cf. [Katkhuda et al.(2010)Katkhuda, Dwairi, and Shatarat] for further details). The damaged element modelled as two EBB joined through a spring is eventually yields a 6×6 matrices for stiffness and mass which further is condensed to 4×4 matrices by removing the dofs corresponding to the spring.

The system is further estimated using Bayesian filtering approach (Particle filtering to be specific) where in the index of the damage element, location of the spring with respect to the element and its rotational stiffness is estimated as states in order to detect the location and severity of the damage in the actual beam.

3. NUMERICAL ANALYSIS AND DISCUSSION

Table I. Specification of the beam

Length (m)	Width (m)	Height(m)	Modulus of elasticity (GPa)	Density (kg/m^3)
0.8	0.02	0.02	181	7860

(a) Actual beam with two edge cracks

(b) Cracks modelled as mass-less spring

Figure 2. Schematic diagram of the modelling approach

A cantilever beam is chosen for the numerical analysis with two edge cracks (c.f figure 2). Material and geometric properties of the beam are detailed in table I. Subsequently, the cracks are replicated with rotational springs as mentioned before. The depth and location of the cracks from left end of the beam are defined as a_i and x_i. The schematic of the modelling is presented in figure 2 Without considering any damping effect the governing equation of the beam dynamics under external forcing $\mathbf{P}$ can further be presented as,

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{P} \tag{2}$$

with $\mathbf{M}$ and $\mathbf{K}$ being mass and stiffness matrices (for further details cf. [Katkhuda et al.(2010)Katkhuda, Dwairi, and Shatarat, Lee(2009)]) and $\mathbf{x}$ is the displacement vector.

Table II. Specification of Crack depth and location in the beam

$a_1(m)$	$a_2(m)$	$x_1(m)$	x_2
0.004	0.006	0.255	0.545

First three natural frequencies of cantilever beam extracted from the numerical model are compared with the experimental result as presented in [Lee(2009)]). Two edge cracks causing of 20% and 30% damage equivalent to stiffness reduction factors of 20 and 17.5 in the beam are considered (cf. Table II) and the resulting frequencies are compared in Table III demonstrating that such modelling strategy can safely be employed for model-based damage detection approach.

Table III. Comparison of first three frequencies of beam.

Undamaged Beam			Cracked Beam		
Experimental	Numerical	Error	Experimental	Numerical	Error
24.18	24.22	0.18	24.04	24.13	0.36
152.10	151.81	0.19	149.27	150.96	1.13
424.46	425.09	0.15	409.29	420.40	2.71

3.1. Proposed filtering based damage detection approach

Parameter estimation problems are generally nonlinear inverse problems. Within this scope, particle filtering based recursive estimation of parameters like damage location and severity are observed to effective. To execute filtering technique in discrete time domain, a state space model is required with parameters are estimated as augmented states drawing inference from measured response [Sen et al.(2018)Sen, Crinière, Mevel, Cérou, and Dumoulin]. Present study employs similar PF based estimation approach wherein damage element, location of the spring and its rotational stiffness is assumed to be the states to estimate from the measured collocated/non-collocated responses.

REFERENCES

[Chasalevris and Papadopoulos(2006)] Athanasios C Chasalevris and Chris A Papadopoulos. Identification of multiple cracks in beams under bending. *Mechanical systems and signal processing*, 20(7):1631–1673, 2006.

[Ghadami et al.(2013)Ghadami, Maghsoodi, and Mirdamadi] A Ghadami, A Maghsoodi, and HR Mirdamadi. A new adaptable multiple-crack detection algorithm in beam-like structures. *Archives of Mechanics*, 65(6):469–483, 2013.

[Lee(2009)] Jinhee Lee. Identification of multiple cracks in a beam using vibration amplitudes. *Journal of Sound and vibration*, 326(1-2):205–212, 2009.

[Eur(2003)] *Eurocode 3 : design of steel structures.* BS EN 1993- I-X:2003. BSI, London, 2003.

[Aswal et al.(2022)Aswal, Sen, and Mevel] Neha Aswal, Subhamoy Sen, and Laurent Mevel. Strain-based joint damage estimation approach robust to unknown non-stationary input force. *Structural Control and Health Monitoring*, page e2999, 2022.

[Katkhuda et al.(2010)Katkhuda, Dwairi, and Shatarat] Hasan N Katkhuda, Hazim M Dwairi, and Nasim Shatarat. System identification of steel framed structures with semi-rigid connections. *Structural engineering & mechanics*, 34(3):351, 2010.

[Sen et al.(2018)Sen, Crinière, Mevel, Cérou, and Dumoulin] Subhamoy Sen, Antoine Crinière, Laurent Mevel, Frédéric Cérou, and Jean Dumoulin. Seismic-induced damage detection through parallel force and parameter estimation using an improved interacting particle-kalman filter. *Mechanical Systems and Signal Processing*, 110:231–247, 2018.