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Prognosis for ballistic sensitivity of pre-notch in metallic beam through mesh-less computation reflecting material damage

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ABSTRACT

Pre-existing discontinuity in the form of notch in a clamped metallic beam can significantly alter its final response and failure pattern under a dynamic impact event. The extent of the notch's influence and sensitivity of its underlying parameters are numerically investigated in this work. Based on Smoothed Particle Hydrodynamics (SPH), a computational framework is developed which can account for material damage and possible moving physical discontinuity due to propagation of crack from the notch location. The numerical model is first validated with experimental evidences from literature and then further explored to establish a mechanism to estimate the precise effects of each of the controlling parameters that may affect dynamic response of clamped beam under impact. Movement of plastic flow and its interaction with geometric irregularity causing localised plastic deformation is studied. Finally a potential deterministic approach is followed to predict the critical velocity for a beam with particular impedance and with certain pre-notch geometry.

1. Introduction

Structural response of beams has got innumerable investigating treatments for its elementary characteristics on overall influence of real life structures. And impact loading on clamped beam constitutes a distinctive vast field for dynamic behaviour of various target assemblies. Particularly the metallic materials exhibit a global ductile mode of deformation dominated by plastic dissipation under sufficiently strong impulse (Yu and Jones, 1997). The formation of plastic hinges or their subsequent motions along axis of the beam during the primary bending duration, and elastic oscillations about the mean position are generally governed by the elastic and plastic wave propagation within domain of the continuous material, bounded by geometrical boundary. Their interaction at the elastic–plastic interface accentuates the kink in the geometric profile leading to finite stress concentration at the hinges (Ruan and Yu, 2003).

If a discontinuity or imperfection in the form of notch exists within the path of this wave motion, it influences the response pattern quite dramatically. It may act as the initiation site for a stationary plastic hinge that absorbs a significant portion of the impact energy (Petroski, 1984). Localisation of plastic strain around the discontinuity manifests itself into a different mode of deformation. Even the ultimate failure behaviour gets re-oriented due to crack extension from the notch tip rather than the crack initiation from flawless homogeneous region. The precise effect of pre-existing notch depends on notch geometry (size and shape) and its location in addition to the other obvious parameters (which also influence the flawless target behaviour) such as material characteristics, boundary condition, loading details, inertial and natural frequency band of the system.

While there exist extensive literature on beams under impact (Yu and Jones, 1989; Shen and Jones, 1993; Teng and Wierzbicki, 2005), few attempts have been made to study the effect of pre-existing notch on the ballistic response of beam. Kumar and Petroski (1985) developed an analytical model to estimate the peak deformation of pre-notched simply-supported beam. In their model the notch is assumed to be stable i.e. no further growth of the pre-existing notch takes place. The parametric investigation on the governing equations revealed that rotation at hinge locations vary greatly with reduction in moment capacity due to presence of notch particularly in heavy-mass impact. Moreover this reduction in plastic moment capacity is also influenced by the elastic response, though not in similar scale as that of large in-elastic strain. In Petroski and Verma (1985), the stability of a notch in impulsively loaded cantilever was investigated through a simplistic analysis supported by experiments. It was observed that the presence of pre-notch may cause additional plastic hinge at the notch depending on the depth and the location (near the support or at the impact point or at the mid-way between support and impact zone) of the notch.

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The analytical models as mentioned above could emphasise the very important feature of multiple-hinge mechanism. However they only give a qualitative representation of effect of pre-existing notch on overall behaviour of the beam. Moreover since the notch is assumed to be stable, the analytical models do not give a comprehensive information about the possible crack initiation and propagation from the tip of the notch leading to complete failure – which are the common phenomena encountered in pre-notched beam under projectile impact.

Experiments, on the other hand, may provide a realistic means to investigate those effects of physical discontinuity on the failure pattern. Few experiments on pre-notched beam have been performed and reported in the literature. Woodward and Baxter (1986) performed experiments on notched free-free steel beam and showed that the angle of bend is insensitive to notch depth. In Liu et al. (2013), it was showed through experiments and LS-Dyna simulation that the global deformation profile until failure is strongly dependent on amount of restraint provided at supports. A set of comprehensive experiments on pre-notched clamped beam with different sizes and locations of notch are given in Chen and Yu (2004) and Harsoor and Ramachandra (2009). The major observation was that the presence of notch may change the dynamic behaviour of the beam from global ductile to local strength failure. Moreover the effect of pre-notch on the transient response of the beam significantly depends on its location.

Whereas the pre-notch characteristics (eccentricity, location, depth, width etc) are found to influence the onset of different failure modes (Chen and Yu, 2004), more precise characterisation is needed for notched beam behaviour to estimate the threshold energy to destabilize the structure and the energy absorbed by different counter-competing yet simultaneous dissipative mechanisms. Potential use of notch as a crack arrester at a desired location or the significant strength degradation due to its presence can be more efficiently studied based on that characterisation. However this characterisation is not achievable only through experiment, as the correlation of the experimental observations with meaningful interpretations becomes difficult due to scatter in measured data, noise in the form of obliquity of striker motion or support slippage. Moreover, although being accurate, experiments provide a cumulative effect of all involving parameters which are difficult to be isolated. Brevity of the whole impulse event makes the meaningful data extraction quite difficult and therefore numerical methods are gaining momentum in this regard. While the real-life tests give the ultimate failure pattern, the entire time history of different field variables in different phases of deformation and accumulation of strain at zones of irregularity can easily be captured through a numerical simulation (Villavicencio and Soares, 2012; Johnson et al., 2000).

In the present context, a numerical technique must be capable of dealing with large localised deformation, moving physical discontinuity owing to crack propagation and breakage. Smoothed Particle Hydrodynamics (SPH) (Lucy, 1977; Gingold and Monaghan, 1977; Libersky et al., 1993) provides a platform for modelling such phenomena effectively. SPH has been successfully applied to a wide range of problem related to impact mechanics (Benz and Asphaug, 1995; Liu and Liu, 2010). Chakraborty and Shaw (2013) enhanced the SPH technique with the concept of pseudo-spring for modelling arbitrary evolving crack in solids. The pseudo-spring SPH has ability to reflect material strength and progressive damage evolution (leading to open crack) even in material-independent kernel estimating framework without relying on any crack path tracking and discontinuous enrichment of basis function (Rabczuk and Belytschko, 2004; Rabczuk and Zi, 2007). Herein a particle is allowed to interact only with its immediate neighbours. A network of springs among the interacting particles is then assumed. These springs only stores the interaction definition (undamaged and/or damaged) and do not impose any additional stiffness to the system. Damage accumulates only in the "pseudo-spring", not in the particle itself. Initiation of a crack is simulated by a severance of the connecting springs during continuous damage evolution depending on the properties of the parent material. The pseudo-spring strategy has been successfully employed to investigate the growth of pre-crack at interface of bi-material system (Chakraborty and Shaw, 2014). Also this strategy proved effective in investigating physical real effects in Parkes cantilever problem (Shaw et al., 2015) such as plastic shearing close to projectile and refined treatment of the penetration mechanics.

In the present study the pseudo-spring SPH is adopted to investigate the effect of notch and its underlying parameters on the ballistic response of clamped beam. The pseudo-spring analogy and its integration with standard SPH framework to cater for material damage is demonstrated in Section 2. The computational model is then validated through some experimental results (Chen and Yu, 2004) in Section 3. The tensile tearing tendency at supports and punching tendency at impact zone in flawless beam are investigated in Section 4. Next in Section 5, plastic work localisation, t hrough-thickness-crack-propagation and different failure modes for pre-notched beam are studied. Finally a potential deterministic approach to estimate the ballistic limit is demonstrated exclusive of real life uncertainties such as obliquity and eccentricity in impulse loading, inherent material flaws, partial fixity at support *etc*. This approach is employed in Section 6 to identify the sensitivity of notch's width, depth and location on ballistic performance of the clamped beam. Conclusions are drawn in Section 7.

2. Numerical modelling of damage and material separation

Material discontinuity is the main challenge to reckon when estimating the physical function's time evolution through kernel derivative. The difficulty is attributed to the fact that – in the presence of any physical discontinuity, the kernel looses one of its essential properties, viz convexity – and consequently one of the main premises of kernel estimate is violated. Moreover, when damage initiates and evolves, the interactions between particles no longer remain same. Therefore, the kernel function, through which particle interaction takes place, must be able to account for such varying interaction due to material degradation. It must also account for physical discontinuity that may occur when damage becomes a fully open crack. The variation in slope of the kernel, in a way, accounts for that varying interaction between particles leading to no interaction when one particle leaves the influence domain of the other. However since kernel functions are chosen independent of the material strength, such changes in inter-particle distance and subsequent alteration in amount of force transfer does not reflect the real material behaviour when it undergoes damage and failure.

The pseudo-spring analogy (Chakraborty and Shaw, 2013) is a way out of the above mentioned limitation of material-independent kernel estimate, commonly used in SPH simulation of fracture (Johnson et al., 1996; Mehra and Chaturvedi, 2006). In this section, an SPH framework, enhanced with the pseudo-spring analogy for modelling damage and subsequent material separation is discussed. In order to have a better appreciation of the present formulation and also for the completeness a brief account of standard SPH formulation is given in Appendix A. For more comprehensive information readers are also referred to Monaghan (2005).

2.1. Pseudo-spring analogy

First distinctive feature of the pseudo-spring SPH vis-a-vis the standard SPH is the definition of neighbour. Here, a given particle