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A methodology for predicting high impact shock propagation within bolted-joint structures

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ABSTRACT

The development of accurate and efficient numerical methodology for predicting shock propagation in bolted-joint structures is an important problem. Bolted joints have multiple nonlinearities such as friction, contact stiffness, and impact loading. Joint models are typically complex and computationally expensive. These problems become even more challenging when the bolted joint is experiencing high impact shock. This paper examines the issues associated with developing an accurate model for shock propagation within bolted joint structures. A combined Lagrangian-SPH (Smooth Particle Hydrodynamics) approach is used to develop a finite element simulation that can capture both the physical damage of the structure as well as the shock propagation across the bolted joint. This modeling approach is shown to produce favorable results when compared with experimental data from ballistic impact testing of bolted joint structures with a two-stage light gas gun.

1. Introduction

Bolted joints are a common type of fastener that is used in most applications because of the ease to assemble and disassemble components. Bolted-joint structures that are subject to high impact loadings such as military vehicles where load can be initiated by projectile impact or blast require special consideration. These shocks can have serious effect on occupants of the vehicle as well as on electronic equipment within the vehicle. Mechanical joints have complex nonlinear behavior because of the material characteristics, geometry of the bolted components, type, size, and arrangement of the bolts, and the nature of the load. It is almost impossible to model or test the entire equipment because of the computation and experimental limitations. Therefore, it is important to understand the physics of shock transfer through bolted joints.

The following is a brief overview of some of the research conducted in this area. Mattern et al. [1] studied wave propagation in T shaped structures. The structure, discussed in this research is a steel construction of top–hat profiles and sheets, connected with spot welds, which is impacted by a metal ball at the top. The complex behavior of bolted joints plays an important role in the overall dynamics of the structure. This complex behavior can be effect of slip. Gaul and Lenz [2], focused on estimating the energy dissipation in bolted joints associated with micro slip and macroslip regimes. Kess et al. [3] developed a finite element model to simulate energy dissipation through joints. Lobitz et al. [4] compared different modeling technique to predict the energy dissipation due to slip. Reid and Hiser [5] had done a detailed modeling of bolted joints with slippage to study the roadside structures. They studied discrete-spring based clamping model with rigid parts and stress based clamping model with deformable elements to determine joint slippage behavior.

The slip mechanism also causes damping in the system. Gaul and Nitshe [6] studied the nonlinear transfer behavior of frictional interface and the damping mechanism in joints. Eskandaraian et al. [7], developed a finite element model to simulate the slip base bolted joint in a sign support beam. Wentzel and Olsson [8] created a finite element model that incorporated coulomb friction to study the frictional and plastic dissipation in joints and compared the results with experiments.

Preload plays an important parameter in joints. It affects the dynamic response of the whole system. There has been number of studies done on effects of preload on static response. Park et al. [9], discussed preloading of core bolt of a vehicle rubber mount, which is subjected to impact. Schiffner and Droste [10] showed the simulation of pre-stressed screw joints in complex structures such

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as flywheel using truss and beam elements instead of 3-D volume elements. Esmailzadeh et al. [11] analyzed the preloaded joints on decaying pressure. Damping through bolted joints was considered in modeling this problem. Duffey [12] developed a simple spring-mass model for closure bolting systems, including the effects of bolt pre-stress. An analytical solution was developed for the case of an initially peaked, exponentially decaying internal pressure pulse acting on the closure. Duffey [13] presented bounding, closed-form solutions for selecting the bolt preload for a square, flat plate closure subjected to a pressure pulse load. Pilkey et al. [14] tried to develop a robust, practical procedure to identify damping matrices for structures modeled by linear viscous damping. Impact hammer was used for this purpose. Benedetti et al. [15], studied the interference damping caused by micro slip in bolted joints when subjected to pyro-shock. Damping was included in the finite element model as a function of the Coulomb friction force in the interface. Effect of bolt tightening on the frequency is also discussed. O'Toole et al. [16] compared different finite element modeling techniques for applying preload on joints.

Feghhi [17] studied shock propagation in bolted structures and discussed several error analysis techniques to compare two time signals. Nakalswamy [18] showed that different preload modeling procedure for dynamic finite element analysis and compared with experimental results. The fixtures were induced to low and high level impacts using hammer and one-stage gas gun respectively. Semke et al. [19] studied the dynamic structural response of piping systems and effective analysis techniques were recommended to assess the influence of a bolted flange with an elastic gasket. They concluded that the influence of an elastic gasket is minimal for dynamic loadings. Kwon et al. [20] presented a finite element analysis of bolted structures for static and dynamic loading. They developed three kinds of models for structures with bolted joints: detailed model, practical model and simple model. Based on the applications, one of these models can be selected for stress analysis.

There has been little or no work done on joints when impacted at hypervelocity. Hypervelocity studies are generally done for testing materials which are used for armor and space vehicles. On the other hand, there has been huge amount of research to understand the physics behind impact at sonic velocity and explosive impact for different materials. There are several limitations in understanding and modeling hyper-impact. Since the shock wave travels through the material faster than the elastic wave speed, it is very important to understand the physics of the impact first. There is a difference in the way the material fails from a hypervelocity impact when compared to a regular impact. These high speed impacts produce inelastic collisions causing permanent deformations to both the bodies. Rolsten and Hunt [21] showed that huge amount of heat and radiation is generated from the impact as the bodies collide.

Simulation of projectile penetration of targets requires a numerical technique that allows large magnitudes of deformation in the material. This type of problem is typically difficult to simulate. If a Lagrangian approach is used, the mesh undergoes huge deformation, which typically causes mesh instability issues. One of the most common methods used to avoid mesh distortion is material erosion technique. This technique removes the distorted elements from the simulation based upon user-defined failure criteria such as defining the failure strain of the material. However, there are no general guidelines for defining these criteria. The other most common numerical technique for simulating large deformation problem is Eulerian approach. The main problem with this approach is mixing of materials when the projectile and target deform.

A more recent numerical approach for large deformation problem is Smooth Particle Hydrodynamics (SPH), which is a new class of numerical method that was developed particularly for large deformation problems. SPH is a meshless Lagrangian method that doesn't not require a numerical grid or element to calculate spatial derivative, which enables SPH method to avoid mesh tangling and distortion. In SPH, a set of particles represent the solid geometry. Each particle represents an interpolation point for which all properties are known. Nodal forces, energy and pressure are computed between each particle with regular interpolation function known as smoothing length. Hayhurst and Clegg [22] performed a number of hypervelocity impact simulations on aluminum plates using SPH technique. Schwer [23] compared Lagrangian, Eulerian, and SPH simulation methods with experimental data. They concluded that for high impact and high deformation analysis, SPH has more advantages when compared to other method. Faraud et al. [24] showed that SPH method has few limitations like mesh stabilization, global energy, incorrect plastic estimation, maximum pressure overestimation pressure fluctuation with nearby particles and heavy computational time. Jackson et al. [25] studied the mesh refinement issue with SPH particle. The simulation was compared with experimental data on fuselage section of an aircraft. Coarser mesh yielded better result when compared with finer mesh. They concluded that by simply refining the mesh density doesn't yield better results and that the mesh sizing is dependent on problem formulation.

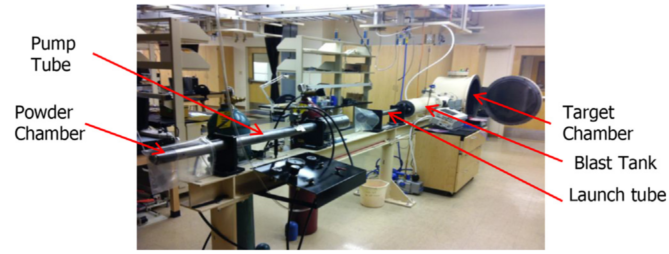

Fig. 1. Two-stage light gas gun at UNLV.

The objective of this research is to better understand how high levels of shock are transmitted through bolted joints. High levels of shocks can be generated by hypervelocity impact. Generally hypervelocity impacts are defined as impact velocity on the order of or greater than the impacting material wave speed. The complexity in designing bolted joints under these conditions lies in the limitations of available methods to characterize their behavior. Typical factors that affect the response of a bolted joint include, preload (bolt tightening), intensity of the impact, and damping within the joint. The aim of this work is to develop an accurate model for analyzing and predicting shock propagation across bolted joints.

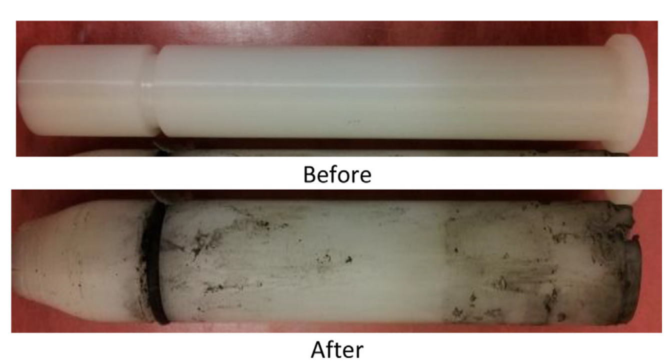

Fig. 2. Piston.