An Approach for Modeling Shock Propagation Through a Bolted Joint Structure

Pouya Shojaei, Mohamed Trabia, Brendan O'Toole, Jed Higdon
Department of Mechanical Engineering, University of Nevada, Las Vegas
Las Vegas, NV

Abstract

Impact loading is typically characterized by a relatively large load happening over an extremely short duration and inducing broad range of vibration frequencies. Standard design approaches of bolted joints based on static or quasi-static criteria may not be effective under these conditions. This study focused on simulating a drop-weight tower experiment where a free-falling mass impacted a target plate, which was bolted to a cylindrical structure. An accelerometer was used to record transmitted acceleration to the cylindrical structure. An approach for simulating the shock propagation was proposed using LS-DYNA® Explicit finite element code. To reduce computational time, thread was not included. Instead, bolts were represented as cylinders with cross-sectional areas equal to the tensile stress area of the bolts. The results showed good agreement between the finite element and experimental results.

Nomenclature

A	Simplified J-C model input constant
A_t	Tensile stress area
b	Number of threads per inch
B	Simplified J-C model input constant
C	Simplified J-C model input constant
d_n	Nominal bolt diameter
E	Young's modulus of elasticity
E_K	Kinetic energy
ETAN	Tangent modulus
F	Clamped force
FS	Static coefficient of friction
FD	Dynamic coefficient of friction
g	Gravitational acceleration
h	Drop height
K	Torque variable (Nut Factor)
m	Mass
n	Simplified J-C model input constant
PSFAIL	Failure strain
SIGY	Yield strength
T	Tightening torque
V	Impact velocity
Y	Poisson's ratio
$\overline{\varepsilon^p}$	Effective plastic strain
$\dot{\varepsilon}^*$	Normalized effective strain
ν	Poisson's Ratio
ρ	Density
σ_y	Flow stress

1. Introduction

Industrial structures are subjected to various kinds of loads, such as static, dynamic, environmental, etc. While the behavior of structures under static and quasi-static behaviors is well-understood [1], [2], [3], responses to impact loading merits further study [4], [5]. Bolted flange joints are commonly used in many industries because of their ease of assembly and maintenance; failure of these joints can result in costly damage.

Some studies have focused on the dynamic responses of bolted joints. Semke et al. [6] studied the dynamic structural response of piping systems experimentally and numerically to assess the influence of a bolted flange with an elastic gasket. Oldfield et al. [7] developed a finite element model to study the friction phenomena taking place in a bolted joint subjected to dynamic loading. It was found that for a fixed bolt preload, increasing the applied torque led to an increase of energy dissipated per cycle. Mersch et al. [8] developed a numerical approach for modeling the behavior of fasteners under dynamic loads. The fasteners were modeled with two low-fidelity approaches, and the analysis under-predicted the failure in the fasteners. Luan et al. [9] proposed a simplified two-degree of freedom nonlinear dynamic model using bi-linear springs to represent the mechanical properties of the joints. Couchaux et al. [10] proposed a mechanical model for non-preloaded bolted connections, taking into account the contact interactions between the opposite flanges. Two types of contact elements, i.e., flexible contact elements between the flange and the bolt head and rigid contact elements between the flange and the fictitious flange, were evaluated. Kess et al. [11] conducted a study on the effect of stress distribution in bolted lap joints on energy dissipation, and the plausibility of standard friction models to describe the experimental phenomena. They concluded that the equivalent linear damping in a lap joint was a function of the bearing area, over which micro-slip could potentially occur. Gaul and Lenz [12] considered the effects of micro and macro-slipping on energy dissipation within bolted joints. They studied the nonlinear influence of the connections by the rapid decay of free vibrations of the assembled structure in two dimensions. O'Toole et al. [13] considered five different approaches for modeling the bolt pretension, i.e., force on bolt and nut, force on bolt shank, interference fit, thermal gradient, and initial stress. They investigated their effects on the dynamic response of bolted joints and asserted that the thermal and initial stress methods were the most suitable techniques for non-linear dynamic problems. Kim et al. [14] investigated four kinds of finite element models for modeling a structure with bolted joints: a solid bolt model, coupled bolt model, spider bolt model, and no-bolt model. They observed that the solid bolt model, modeled by using 3D solid elements and surface-to-surface contact elements between head and nut and flange interfaces, provided the most accurate responses, compared with the experimental results.

In earlier studies, shock propagation across the bolted joint structure under impact loading, as well as two different approaches for modeling the bolt-nut assembly were evaluated [15], [16]. However, other factors affecting the dynamic response of bolted joints under impact loading, including the friction between the clamped components, may merit further investigations. In this work, drop-tower experiments were conducted, and an approach for the computational modeling of the experiment was proposed. Different cases of the static and dynamic coefficient of friction at the clamped components' contact surfaces were considered based on the proposed values in the literature. Experimental and simulation results were compared.

2. Experimental Study

2.1 Drop Weight Tower

A Dynatup Instron 8250 drop-weight tower was used to perform experimental low-velocity impact testing, Fig. 1 (a). Drop heights of 0.0508 m to 1.016 m can be achieved. The mass of the drop assembly can be adjusted by changing the support plates in the crosshead. The weights can be varied from 2.5 kg to 45.3 kg. In this study, a drop weight of 4.5 kg was used. A cylindrical impactor was attached to the weights through an impactor holder, Fig. 1 (b). The masses of the impactor and impactor holder were 0.10 kg and 0.25 kg, respectively. The drop velocity and impact energy of the weights are calculated using Equations (1) and (2), respectively:

$$V = \sqrt{2gh} \qquad\qquad (1)$$

$$E_K = \frac{1}{2}mV^2 \qquad\qquad (2)$$

2.2 Test Setup

The test fixture was composed of a structural steel cylinder with an internal flange and a lid. These two components were connected using four SS 304 8-18 screws with the base, shown in Fig. 2 [17]. As the impactor contacted the lid, tensile loading was induced in the four bolts. All bolts were tightened using a torque wrench at 1 Nm to ensure uniform pressure between the lid and the flange in the tangential direction. The base had a 1/4-28 threaded through hole at the center, connected to the load cell. The load cell was attached to the base of the drop-weight tower.
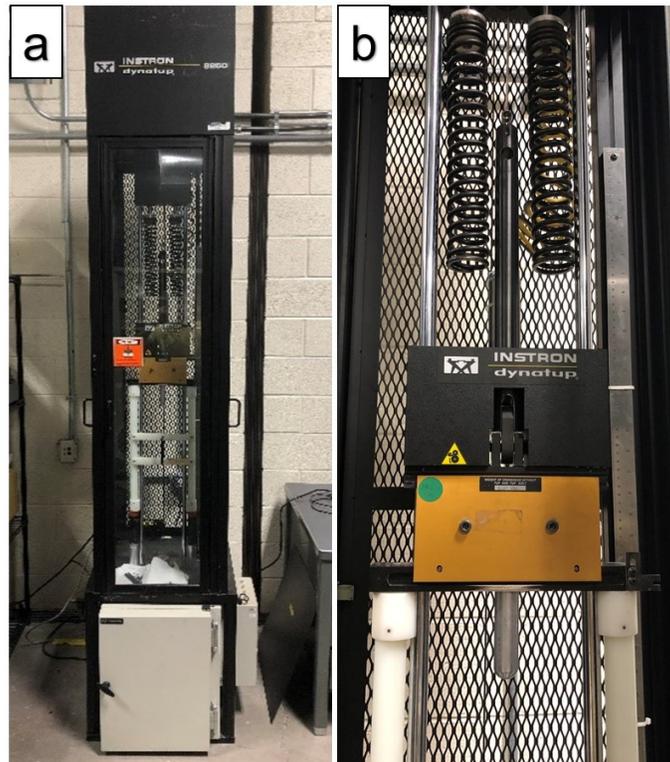
Fig.1: (a) Drop-weight tower (b) Impactor assembly

The experimental test signals were recorded by a Dytran 3200b accelerometer. The drop weight height was 0.0508m and the tests were repeated three times. The accelerometer's information is summarized in Table 1. Acceleration signals were filtered using a low-pass Butterworth filter with a cut-off frequency of 8000 Hz. Experimental results are shown in Fig. 5.

Table 1: Dytran 3200B Accelerometer Information

Performance	Sensitivity ($\pm$ 10%)	Measurement Range	Resonant Frequency	Frequency Range ($\pm$ 10%)	Sensing Element	Sensing Geometry	Mounting	Electrical Connector
Units	0.05 (mv/G)	$\pm$ 70,000 G	>90 kHz	0.35 to 10,000 Hz	Ceramic	Shear	¼" – 28 mounting studs	10 – 32 micro-coaxial

Fig. 2: The test fixture

3. Finite Element Study

A finite element model was developed to investigate the response of the bolted flange connection under impact loading. The model included several features with the aim of speeding computations without sacrificing accuracy. An explicit solver of the LS-DYNA R8 Revision 95309 [18] finite element code was employed to develop the computational model. All of the computations were done on a 64 GB, 48 core Linux server. The time steps of the simulations and the total simulation time were 0.5 μs, and 2.5 ms, respectively.

3.1 Model development

The finite element model had the following components: weights, impactor holder, impactor, target, target holder, fixture, bolt head, shank, nut, and load cell. Since the experimental setup had two planes of symmetry, only a quarter of the entire setup was modeled. Various mesh densities were applied to assess the mesh stability analysis, especially within the vicinity of the impact location. The impactor, neighboring region on the lid, bolt head, shank, and nut had denser meshes. The bolt head, shank, and nut were modeled as separate parts. Fig. 3a shows the finite element model. A zoomed view of the fixture is shown in Fig. 3b. A clearance was applied between the bolt shank and the hole, as shown in Fig. 3c. The approximate element sizes range from 0.34 mm to 1.4 mm, and the total number of elements were 558,214. The complexity of modeling thread interaction between the bolts and nuts was avoided. Instead, thread was replaced by smooth cylindrical surfaces on both nuts and screws, whose areas are equal to tensile stress area, calculated based on Equation (3) [19]:

$$A_t = \frac{\pi}{4}(d_n - 0.9743/b)^2 \tag{3}$$

A tied contact between the bolt and nut was implemented. The failure criterion for this contact was based on the shear failure. After trying different values, a *Normal Failure Stress (NFLS)* of 433 MPa was applied to the tied contact keyword, while a *Shear Failure Stress (SFLS)* of 250 MPa was calculated based on Equation (4).

$$\text{SFLS} = 0.577 \text{ NFLS} \tag{4}$$
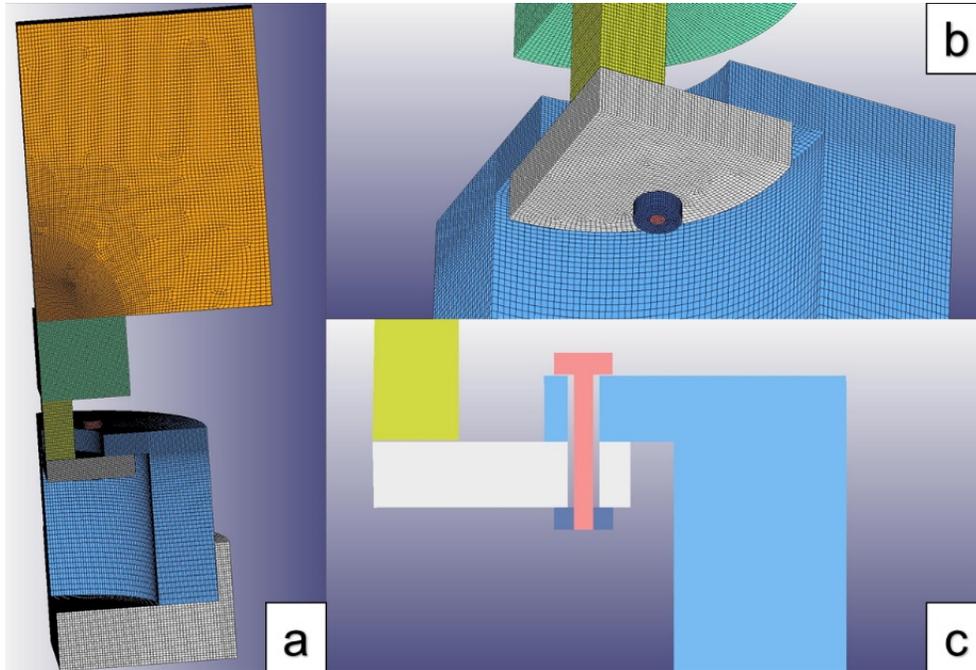
Fig. 3: (a) Finite element model (b) Zoomed view of the fixture (c) Sectional view of the fixture

3.2 Material models

A Simplified Johnson-Cook material model was used for the bolt and nut assembly, as these parts experienced high strain rate effects. On the other hand, all other components were modeled with bi-linear elastic plastic material models. In a Simplified Johnson-Cook model, the flow stress is expressed as:

$$\sigma_y = (A + B\bar{\varepsilon}^{p^n})(1 + C \ln \dot{\varepsilon}^*) \qquad (5)$$

Failure of an element occurs when the effective plastic strain exceeds *PSFAIL*. The properties of the material models are shown in Table 2.

Table 2: Constitutive material models properties used in the simulations [17]

Property	Plastic Kinematic Model (Structural Steel)	Simplified Johnson-Cook Model (SS 304)
LS-DYNA Designation	MAT 003	MAT 098
$\rho(\frac{kg}{m^3})$	7850	7850
$E(Pa)$	200E9	200E9
υ	0.3	0.3
SIGY(Pa)	4E8	-
ETAN(Pa)	9.03E7	-
A	-	3.1E8
B	-	1E9
n	-	0.65
C	-	0.07
PSFAIL	-	0.28

3.3 Definitions of boundary, contact and the bolt preload

Boundary conditions were assigned to reflect the quarter symmetry model. The lower surface of the load cell was fixed. The mass, impactor holder, and impactor were located 0.1 mm above the surface of the fixture. These parts were assigned initial velocity based on Equation (1). The bolt preload caused by the tightening torque was included by applying an Initial Stress Section, which preloads a cross-section of solid elements to a prescribed stress value. The relation between the tightening torque and clamped force is expressed as:

$$T = K \times d_n \times F \tag{6}$$

Assuming K=0.2 and d_n=4.16 mm, the initial stress was calculated as 207 MPa [17]. Automatic Single Surface and Force Transducer Penalty contact definitions were used for the interfaces between the parts. To capture the shear interaction of the bolt and nut at the thread, contact between the shank and nut surfaces was defined using Automatic Surface-To-Surface Tiebreak contact.

4. Results and Discussion

To study the effect of friction between the surfaces of the clamped parts on the shock propagation, five cases were considered; the first case assumed completely smooth frictionless surfaces between the flange and the lid, while the other four cases assumed static and dynamic coefficients of friction ranging from 0.1-0.45 and 0.05-0.3, respectively [20], [21]. The signals were measured at the accelerometer location. These signals were filtered using a low-pass Butterworth filter with a cut-off frequency of 8000 Hz. As seen in Fig. 4, the filtered accelerations were identical in all cases. Therefore, it was seen that the friction between the parts did not contribute significantly in the shock propagation pattern. Therefore, the frictional coefficient of 0.10, which is usually given in the literature for dynamic metal operations, was used for the rest of this study [21].
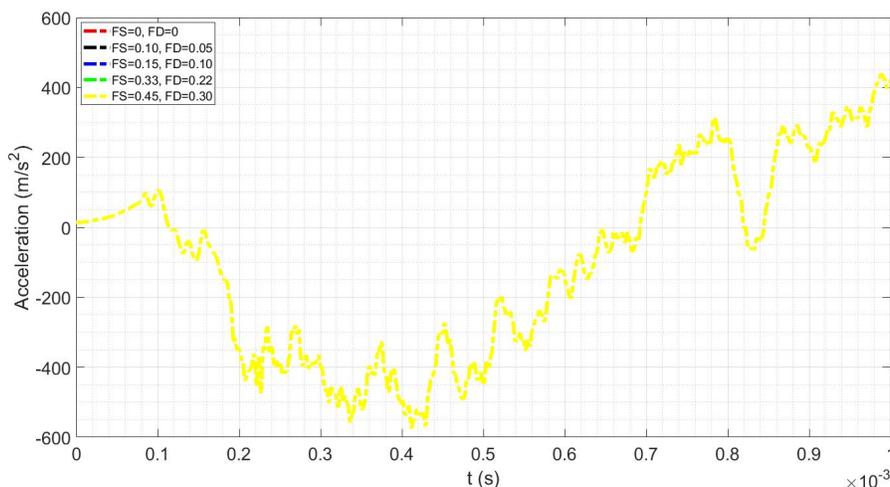
Fig. 4: Comparison of varying static and dynamic coefficients of friction within the finite element model on the shock propagation

The finite element acceleration signal was then compared with the experimental test signals. As seen in Fig. 5, there was a good agreement between the average of the three experimental tests and the finite element signal. Both approaches had a minimum valley, occurring in the range of 0.22-0.55 ms, followed by a relatively steep increase, up to about 1.1 ms. After this acceleration peak, the signals decayed quickly.
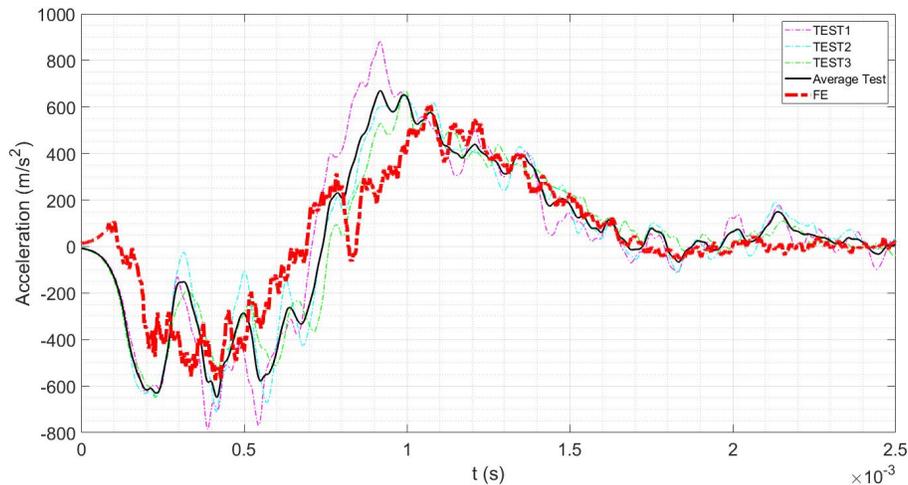
Fig. 5: Comparison of filtered acceleration signal between finite element and experiment

5. Conclusion

The objective of this study was to present an approach for modeling shock propagation through a bolted joint structure under impact loading. To this end, the experimental and numerical simulation of a bolted flange joint were conducted. Different coefficient of friction values were considered at the flange and lid contact surfaces, ranging from 0 to 0.45. The results showed that at this impact loading, shock propagation was not dependent on the friction between the clamped parts. This observation supported the nature of the loading, which applied shear force to the clamped parts. Experimental and finite element acceleration signals were filtered using a low-pass Butterworth filter. Results showed that the proposed finite element model was able to represent the shock propagation through the structure accurately. The verified model can be used for further parametric studies on the structures' design and reduce the need for experimentation. The research may continue with another study focused on investigating bolt behavior at higher impact energy levels.

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