Finite element method for designing HF2V device force capacity

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ABSTRACT

Supplemental energy dissipation devices are increasingly used to protect structures, limiting loads transferred to structural elements and absorbing significant response energy without sacrificial structural damage. High force to volume (HF2V) dampers are supplemental energy dissipation devices, which have previously been designed using relatively low-precision models, creating significant design uncertainty and requiring an inefficient build-test approach. Further, knowledge of the internal mechanics of the lead and bulged shaft, which result in the device force, is lacking, limiting predictive accuracy in device design. This paper presents a more precise, finite-element based, method of predicting device resistive forces based on any given device geometry.

Dimensions for 15 experimental HF2V devices tests are applied to a 2D axisymmetric large-deformation finite element model with adaptive meshing, developed using ABAQUS. Resistive forces are produced during the quasi-static displacement of the shaft within the HF2V devices. Total device force is achieved by summing contact pressure forces including the normal and friction forces on the lead along the shaft. Results of these highly nonlinear, high strain analyses are compared to experimental device force results. The force-displacement plots are made from the force-time response obtained from the finite element analysis.

Model force-displacement plots exhibit good prediction capacity corresponding to experimental results. Errors between model and experimental results for all 15 devices ranged from -8% (over-prediction) to +20% (under-prediction) with a mean absolute error of 5.9%. The hysteresis plots from the FE models match the experimental force-displacement curves. The overall FEM approach is objective, repeatable, and thus generalisable. Low error validates the overall approach, and thus the general modeling methodology for accurate HF2V device design presented.

1 INTRODUCTION

High-force-to-volume (HF2V) devices are proven supplemental, lead-extrusion based, energy dissipation devices that can be applied into structural systems like concrete frames (Rodgers, 2012; Rodgers et al., 2009; Rodgers et al., 2012), braced structures (MacRae et al., 2013), steel moment frames (Bacht, 2011; Mander, 2009), steel connections (Rodgers et al., 2008), beam-column joints (Mander, 2009; Rodgers et al., 2015), joints of frames in large structures (Bacht, 2011; Rodgers, 2010; Solberg et al., 2007) and slotted beam assemblies (Muir et al., 2013; Muir, 2014) for effective damage resilience.

However, their complexity have made them difficult to design precisely to match a specific force capacity. Few analytical models capacities (Parulekar et al., 2004; Rodgers, 2006, 2007; Tsai et al., 2002) and design-based models have been proposed to estimate lead extrusion damper forces (Vishnupriya et al., 2017; Vishnupriya et al., 2018). Prediction of lead extrusion damper forces, stress, and force distribution are essential for device design.

1.1 Finite Element Modelling

Finite element (FE) analysis can be used to simulate complex nonlinear mechanics of device operations and compute resulting force capacities. ABAQUS is an effective software for simulating complex nonlinear mechanics of device operations and computing resulting force capacities (Lesar, 1982). Finite element modelling not only provides a method of determining HF2V device forces but also allows visualization of lead flow and stress distribution inside the devices. Using device-specific material properties and the design dimensions of a device, realistic simulation of HF2V internal lead deformation mechanics within a device, and thus precise estimation of the resistive force of devices of all sizes and capacities can be expected.

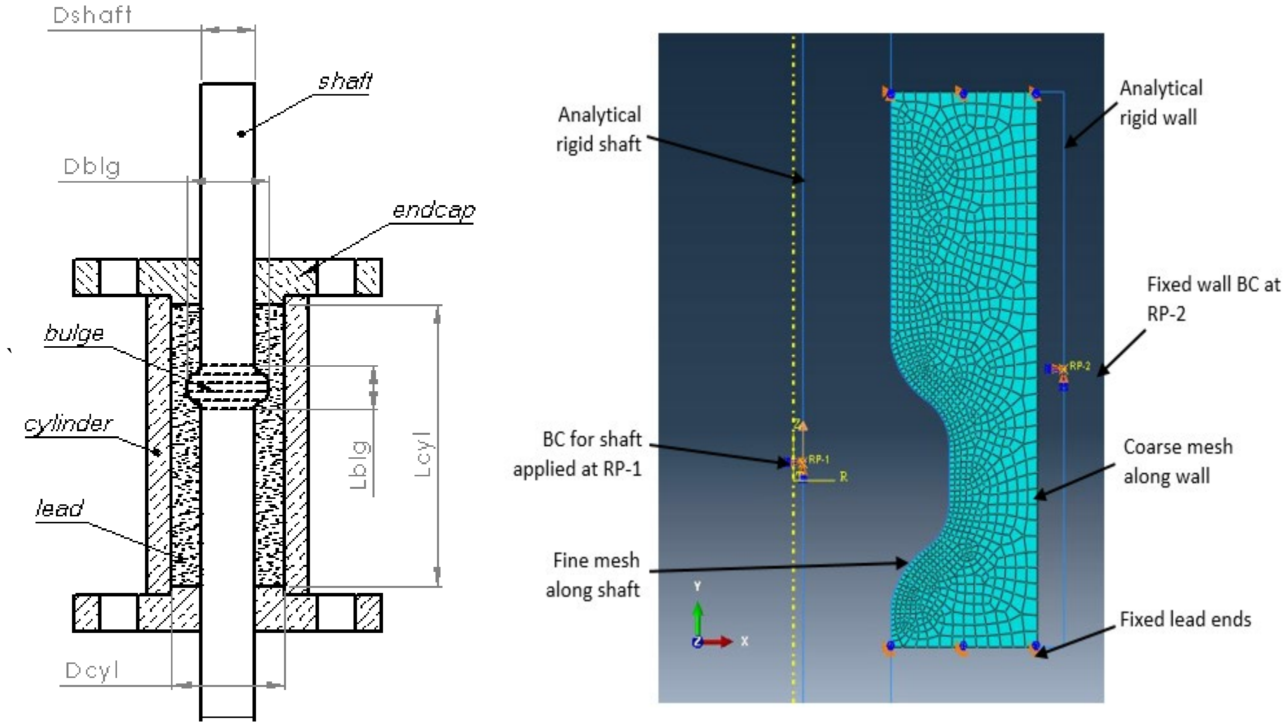
2 METHODS

2.1 Preprocessing method

In an HF2V device a bulged shaft passes through deformable lead material contained in a cylinder, secured by endcaps, shown in Fig 1 (a). During ground motion, the bulged shaft is displaced, and the lead is deformed by extrusion between the bulge and the cylinder walls producing resistive forces.

A 2D model axisymmetric along the vertical axis (Y), is modelled using ABAQUS/CAE (ABAQUS-Users-Manual, 2013). The material properties are assigned only to the deformable lead region (Vishnupriya et al., 2019). A 'fixed' boundary condition (BC) is applied to reference points for the analytic rigid wall representing the lead to containing cylinder interface (RP-2) and the lead to device endcap interfaces, as shown in Fig 1(b).

Quasistatic velocity of 0.5mm/s is applied on the shaft at RP-1, which is allowed displacement only along longitudinal (Y) direction, matching the loading applied within the experimental results against which the model is validated. Kinematic friction formulation is applied for the lead-shaft contact surface, where the friction coefficient (μ) is assumed to be 0.25 (Vishnupriya et al., 2019; Zhou, 2014). Arbitrary Lagrangian–Eulerian (ALE) method is applied on the lead region, meshed with finer mesh along the shaft region where large deformation is expected. The ALE adaptive mesh remaps the nodal positions for each time step (Jin and Altintas, 2012). This re-meshing allows realistic simulation of lead flow within the cylinder and around the shaft, without severe deformation, which may lead to abortion of analysis.



(a) *(b)*

Figure 1: (a) HF2V parts (b) FE model parts, BCs and meshing used for FE modelling

2.2 Postprocessing Method

A force-time response is obtained from the history output of the contact pressure forces including the normal and friction forces on the lead along the shaft. The contact pressure and frictional shear at the lead-shaft interface integrated over the lead area of contact to the shaft are resolved to give the total forces generated at the interface (ABAQUS-Users-Manual, 2013; Rao et al., 2007). The frictional force and the normal contact forces are achieved fromCFS2 and CFN2 respectively. While, the total force produced during the interaction between the moving shaft and deformed lead can be obtained from history output (CFT2) for each time increment. CFT2 denotes the resultant force of tangential and normal stress at contact along Y direction (Mingshun et al., 2011).

'Noise' may be produced in the FEM plots that is due to the stiction or stick- slip mechanism of the lead at the cylinder walls or due to "snagging" along the analytical rigid shaft surfaces (ABAQUS-Users-Manual, 2013). To avoid this issue, filters can be added to the history output after identifying the correct cut off frequencies required for the analysis, such that the peak forces are not modified. Hence, a filter with exponential moving average, using Smooth2 function in ABAQUS is applied. This filter does not alter results, but eliminates small computational errors and noise due to remeshing during each time step. The FEM plots are expected to be similar to the experimental plots from the corresponding device, exhibiting an elasto-plastic yield behaviour

2.3 Device Data for modelling

The geometric dimensions of 15 HF2V devices are as given in Table 1, which are from a range of studies (Latham et al., 2013; Rodgers, 2009; Wrzesniak). D_{cyl} is cylinder diameter; D_{blg} is bulge diameter; D_{shaft} is shaft diameter; L_{cyl} is cylinder length and L_{blg} is length of bulge (Vishnupriya et al., 2017; Vishnupriya et al., 2019; Vishnupriya et al., 2018), shown in Fig 1(a). F_{exp} indicates the experimental peak force attained from experiments.

Table 1: Geometric parameters of HF2V device used for modelling and analysis

Device	D_{cyl} (mm)	D_{blg} (mm)	D_{shaft} (mm)	L_{cyl} (mm)	L_{blg} (mm)
1	89	40	30	110	30
2	89	50	30	110	30
3	89	58	30	110	30
4	66	40	30	130	30
5	66	50	30	130	30
6	50	32	20	50	23
7	50	32	20	70	20
8	60	42	33	160	30
9	50	35	24	100	23
10	70	48	30	75	30
11	54	35	30	160	20
12	54	36	30	160	20
13	54	38	30	160	20
14	40	27	20	100	17
15	62	45	30	155	23

3 ANALYSIS

The FE model approach is applied the same way to all 15 devices of different sizes (Vishnupriya et al., 2018), and force capacities are considered in this study, without any changes. The use of device-specific geometry is the only variation between the analyses. All the pre-processing and post processing steps for the FE modelling and analysis are carried out using ABAQUS.

The total device force (CFT2) is the sum of friction forces (CFS2) and contact pressure (CFN2) forces produced along Y direction at the lead-shaft interaction. This data is generated by ABAQUS during the analysis for every increment. The peak resistive force generated by the HF2V finite element model can be achieved by analysing the total force (CFT2) from time-history output.

The FE model is assessed for its ability to predict experimental device forces by replicating experimental hysteretic force-displacement behaviour. Force-displacement hysteresis plots are automatically generated in ABAQUS for the total resistive force output achieved from the history output (CFT2) at the shaft – lead interaction (ABAQUS-Users-Manual, 2013). The FEM plots are expected to be similar to the experimental plots from the corresponding device. However, strain hardening or softening effect is not expected in the FEM plots as no strain hardening or softening parameters were included in the material properties of lead in the FE modelling method presented.

In addition, the resulting maximum force from the FE analysis of HF2V devices is compared to the maximum force from the experimental forces for the corresponding devices and error is computed using:

$$Error = \frac{|F_{exp} - F_{model}|}{F_{model}} \times 100 \quad \% \tag{1}$$

4 RESULTS

Force - displacement hysteresis plots are made for each device with four representative plots shown in Figure 2. The experimental plots are compared to the plots from FEM results. In Figure 2 (a), FEM plots for Devices 4 and 14 show a very good match with the experimental plots with overall similarity in the plot shapes. In this case, the overall force prediction and hysteresis plots match very well for both the devices in the figure.

The curves in Figure 2 are for loading, but also cover unloading in the opposing direction, which is just the reverse motion for this analysis, and thus give the same curve but reversed.

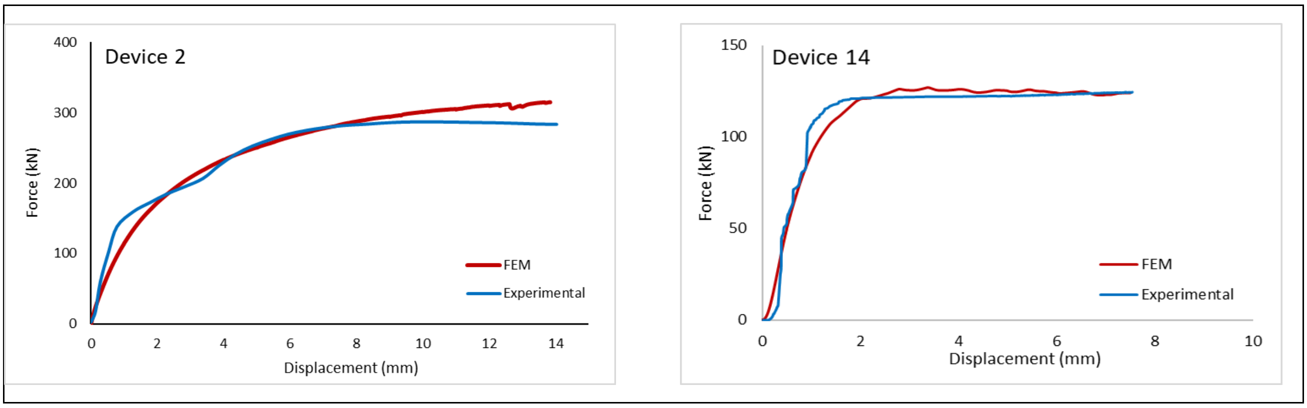


Figure 2 (a): FEM plots matching the HF2V experimental plots

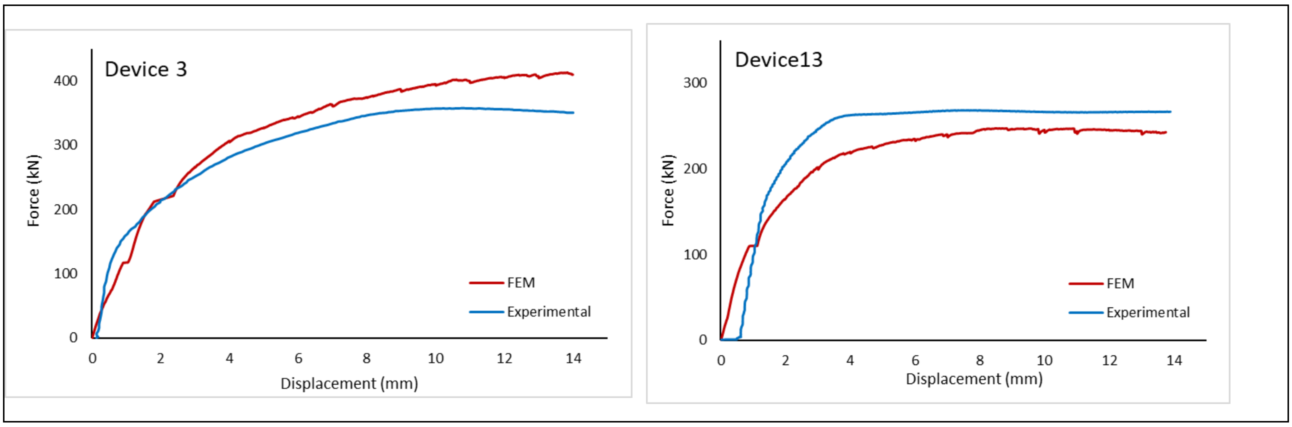


Figure 2 (b): FEM plots in case of over prediction and under prediction for devices

In Figure 2(b), the plots for Devices 3 and 13 show an experimental plot similar to the FEM plots, but the peak forces show some disparity. In this case, the cause is less certain, but likely due to relatively small differences between real and assumed material properties. The forces obtained from the FEM have forces within ±10% for 13 of 15 devices and between ±11-20% for 2 of 15 devices. The comparison between experimental and model forces presented in Table 2 shows that the FE modelling approach is entirely general, objective, and replicable.

The most important aspect of precise device design is the input material parameters help in replicating the actual device operations. Identifying the exact material properties helps to accurately simulate device operations. Some of the errors in the results can be attributed to insufficient device design data and testing data available for finite element modelling, such as the specific device testing velocity, exact bulge profile data, bulge curvature radius, bulge angles, and bulge length. Previous studies suggest these parameters can potentially influence the extrusion forces outcomes (Fereshteh-Saniee et al., 2013; Golondrino, 2012a, b; Lontos, 2008). The understrength of the experimental results as seen for Devices 6, 8, 10 and 13 in comparison to the FEM results can be explained by irregularity in pre-stress and can be addressed by further pre-stressing in manufacture.

Table 2: Comparison of maximum HF2V device forces from experiments and finite element modelling

Device	F_{exp} (kN)	F_{model} (kN)	Error %
1	160	167	-4
2	285	310	-8
3	390	400	-3
4	200	185	-8
5	346	345	0
6	130	125	+4
7	150	152	-1
8	260	245	+6
9	155	155	0
10	250	200	+20
11	170	175	-3
12	200	220	-10
13	260	245	+6
14	125	130	-4
15	190	213	-12

Overall, the resulting finite element modelling approach yields a generic model, which can predict device forces well within the range for all types of HF2V lead extrusion dampers. Therefore, it can be used as a design tool along with the design-based model to obtain the precise force capacity range of the desired device, limiting the need for extensive prototype validation and possible device redesign.

5 CONCLUSION

This study details a large deformation, nonlinear, finite element modelling methodology used in modelling the HF2V lead extrusion dampers, to predict the device force capacity. This method computes the device force automatically using finite element methods and is a reliable tool for design optimization. The FEM predicts with reasonable accuracy within a range of 0%-20% and is generalizable and objective. Additionally, the force-displacement plots from the FE method provide an insight to the mechanisms involved during the nonlinear behaviour of dampers during operation. Thus, the model can be used as a design tool and can be used as a reference of expected HF2V device behaviour and force capacities before manufacturing.

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