GENERALISABLE NONLINEAR FINITE ELEMENT MODELLING FOR HIGH FORCE TO VOLUME (HF2V) DEVICE DESIGN

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Abstract

Supplemental energy dissipation devices are increasingly used to protect structures, limit loads transferred to structural elements and absorbing significant response energy without sacrificial structural damage. Lead extrusion dampers are supplemental energy dissipation devices, where recent development of smaller volumetric size with high force capacities, called high force to volume (HF2V) devices, has seen deployment in a large series of scaled and full-scaled experiments, as well as in three new structures in Christchurch, NZ and San Francisco, USA.

HF2V devices have previously been designed using limited precision models, so there is variation in force prediction capability. Further, while the overall resistive force is predicted, the knowledge of the relative contributions of the different internal reaction mechanisms to these overall resistive forces is lacking, limiting insight and predictive accuracy in device design. There is thus a major need for detailed design models to better understand force generation, and to aid precision device design. These outcomes would speed the overall design and implementation process for uptake and use, reducing the need for iterative experimental testing.

Design parameters from 17 experimental HF2V device tests are used to create finite element models using ABAQUS. The analysis is run using ABAQUS Explicit, in multiple step times of 1 second with automatic increments, to balance higher accuracy and computational time. The output is obtained from the time- history output of the contact pressure forces including the normal and friction forces on the lead along the shaft. These values are used to calculate the resistive force on the shaft as it moves through the lead, and thus the device force. Results of these highly nonlinear, high strain analyses are compared to experimental device force results.

Model errors compared to experimental results for all 17 devices ranged from 0% to 20% with a mean absolute error of 6.4%, indicating most errors were small. In particular, the standard error in manufacturing is SE = ±14%. In this case, 15 of 17 devices (88%) are within ±1SE (±14%) and 2 of 17 devices (12%) are within ±2SE (±28). These results show low errors and a distribution of errors compared to experimental results that are within experimental device construction variability.

The overall modelling methodology is objective and repeatable, and thus generalizable. The exact same modelling approach is applied to all devices with only the device geometry changing. The results validate the overall approach with relatively low error, providing a general modelling methodology for accurate design of HF2V devices.

Keywords: HF2V, lead dissipater; finite element model; energy dissipation; design

1. Introduction

Lead extrusion dampers are supplemental energy dissipation dampers utilizing the hysteretic properties of lead (Pb) to reduce structural response during seismic loading [1, 2]. High Force to Volume Devices (HF2V) are lead extrusion dampers with smaller volumetric size and higher force capacities [3, 4]. The HF2V lead extrusion damper has the following parts: a cylinder; working material (lead) enclosed in the cylinder; a bulged shaft passing through the lead and endcaps to secure the lead within the cylinder.

Resistive forces are produced in the HF2V devices when the bulged shaft is axially displaced through the lead under loading. During axial displacement, lead is deformed plastically and displaced through the annular orifice between the shaft bulge and the cylinder wall and moves behind the bulge. Stresses rise rapidly in the cylinder due to lead deformation by the bulged shaft and frictional forces at the shaft-lead interface. The unique recrystallization property of lead repairs material damage due to the extrusion working process at room temperatures by grain growth and recovery [5], resulting in consistent device behaviour across multiple response cycles without any strain hardening or loss of strength or stiffness. The repeatability and low velocity dependence of HF2V devices make them a suitable choice for achieving improved structural damping [3, 6-9].

However, research focusing on a design methodology for these devices is limited for manufacturing and application [10, 11]. The exact reaction mechanisms generating forces beyond extrusion or bulk/shear modulus of lead are not fully known in an HF2V device, limiting insight and predictive accuracy in device design. Design based models that can precisely predict the HF2V force capacity are very limited [11]. Thus, there is a need for a more detailed methodology to better estimate the device force capacity in the design phase. A general approach without any human tuning or oversight would enable a transferrable design approach, removing any subjectivity or bias that can hinder repeatable use and uptake.

1.1. Finite element modelling

Computer simulations could be used to predict device forces to optimize HF2V device design and performance, which has not been done before. Finite element (FE) analysis is an effective method for simulating complex nonlinear mechanics of device operations and computing resulting force capacities [12, 13]. Finite element modelling allows visualization of stress distributions inside the devices and provide a method of computationally determining HF2V device forces and delineating the contributions to these device forces. To date, there have been simplified HF2V models created and used in design and analysis using finite element [14, 15], but these have been simple and do not provide the level of insight that might be offered through FEA.

ABAQUS is a an efficient FE package for simulating quasi-static, complex contact, non-linear and dynamic problems [16, 17]. 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 device force capacity in the device design phases can be expected.

2. Methods

A 2D axisymmetric model comprising of an analytical rigid shaft, deformable lead and analytical rigid wall was created using ABAQUS/CAE [18]. A 2D model is less computationally intensive than 3D models and is enabled through the axisymmetric nature of the devices. The modelling parameters of the HF2V FE model are as tabulated in Table 1.

The model consists of a fixed wall, moving shaft, and a deformable volume lead. Reference points (RP) are applied on the analytical rigid parts. An Arbitrary Lagrangian–Eulerian (ALE) moving mesh is applied on the deformable lead meshed with fine mesh along the shaft and coarse mesh along the walls. ALE method is used to simulate large deformation problems, allowing a moving mesh along with the moving part [19-21].

The motion of the mesh is only constrained at the boundaries and allowed to move under high strain within these fixed boundaries. The mesh is smoothed constantly to reduce element distortion without changing the number of elements and their connectivity [22]. This re-meshing allows the simulation of lead flow within the cylinder and around the shaft, providing a visual guide to the evolution of stress distributions with changing strain/strain rates in the devices as the shaft moves and the dissipation forces are generated. No meshing is required on the analytical rigid parts [18].

Table 1- Device data used for modelling and analysis

ABAQUS Module		**Model Parameter**		
Parts		Analytical rigid shaft	Deformable lead	Analytical rigid wall
Material properties of lead	Elastic Data	Young's Modulus (E) = 16 GPa	Poisson's Ratio (υ)= 0.44	Density (ρ) = 11340 kg/m^3
	Plastic Data [23, 24]	Plastic Strain	Yield Stress (N/m^2)	
		0	689476	
		0.01	5810000	
		0.02	8963184	
		0.04	12400000	
		0.08	15100000	
		0.12	17000000	
		0.16	18000000	
		0.2	19000000	
		0.24	21000000	
		0.28	22000000	
		0.32	22750000	
Step		Step type : Dynamic Explicit		
		Step time = 1s		
Interaction		Friction type: Kinematic friction		
		Coefficient of friction = 0.25		
Contact		Contact surfaces: Shaft – lead interface and lead – wall interface		
		Contact type: Master-slave formulations		
Boundary Conditions		Fixed end conditions at lead to endcap interface and lead to cylinder wall interface		
		Displacement on shaft along Y direction		
		Velocity of 0.5mm/s at reference point on shaft (RP-1)		
Meshing		Element type: CAX4R/CAX3		
ALE mesh		Frequency = 10		
		Remeshing sweep per increment = 1		
Output		Type : History Output		
		Forces : Contact pressure force and Friction force		

The boundary conditions where the lead working material meets the device endcaps is considered as a fixed boundary. Displacement in Y direction and velocity of 0.5 mm/s is applied on the reference point (RP-1) on shaft and a zero displacement condition is applied on RP-2 as shown Figure 1. A frictional condition is applied between the shaft and the lead using a coefficient of friction of 0.25. The force output from the model is analysed for its accuracy in prediction of experimental device behaviour. The total resistive force from the HF2V devices is calculated by summing the normal and friction force produced during extrusion at the interaction between the shaft and the lead.

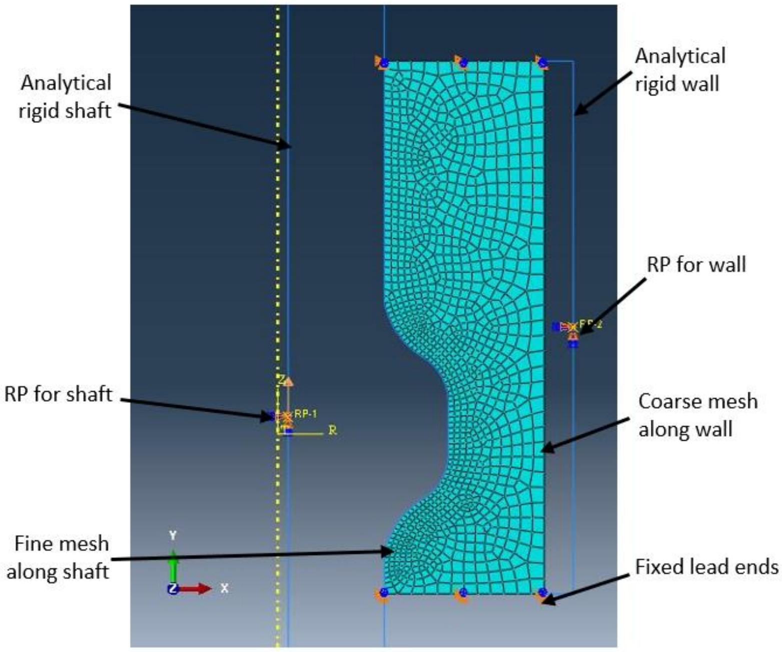

Fig. 1- 2D HF2V model parts, boundary conditions and meshing

The model approach is applied the same way to all 17 devices of different sizes and forces considered in this study, without any changes (other than the device geometry) [11], which are from a range of studies [3, 25, 26]. The HF2V device dimensions are as given in Table 2, where D_{cyl} is cylinder diameter; D_{shaft} is shaft diameter; D_{blg} is bulge diameter and L_{cyl} is cylinder length, shown in Fig. 2. F_{exp} indicates the experimental peak force attained from experiments.

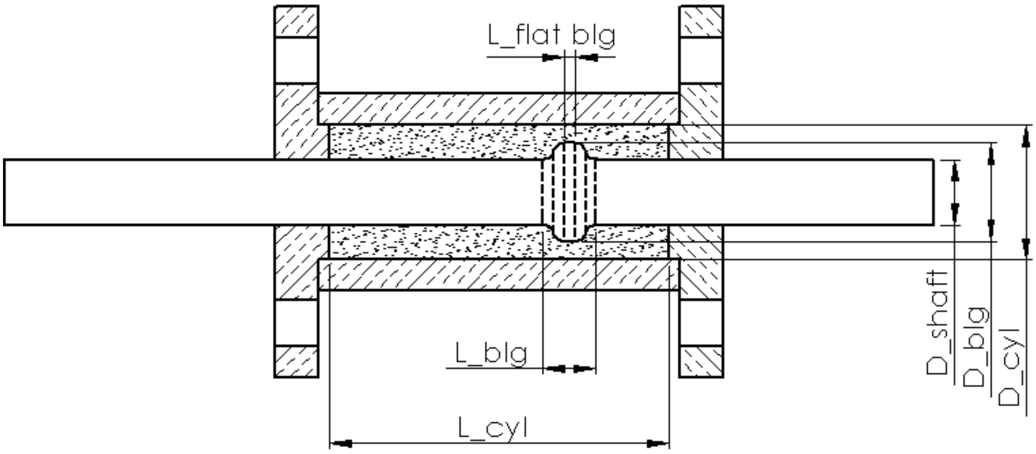

Fig. 2 – Schematic diagram of HF2V damper

Table 2 - Device data used for modelling and analysis

Device	D_{cyl} (mm)	D_{blg} (mm)	D_{shaft} (mm)	L_{cyl} (mm)	L_{blg} (mm)	$L_{flat\ blg}$ (mm)
1.	89	40	30	110	30	5
2.	89	50	30	110	30	5
3.	89	58	30	110	30	5
4.	66	40	30	130	30	6
5.	66	50	30	130	30	5
6.	50	32	20	50	23	5
7.	50	32	20	70	20	2
8.	60	42	33	160	30	3
9.	50	35	24	100	23	5
10.	70	48	30	75	30	5
11.	54	35	30	160	20	3
12.	54	36	30	160	20	3
13.	54	38	30	160	20	3
14.	40	27	20	100	17	3
15.	62	45	30	155	23	5
16.	40	32	20	47	15	0.5
17.	89	62.5	36	250	35	3.5

3. Analysis

Model performance is assessed for its ability to realistically replicate the lead flow in the HF2V devices with shaft displacement. An ideal model simulates the lead flow around the bulge with the displacement of shaft in the HF2V damper. In HF2V dampers, the lead is deformed by the bulge during shaft motion and displaced through the annular orifice between the bulge and the cylinder wall, which then flows behind the shaft and sticks to the shaft behind the bulge. The flow of lead through the annular restriction generates device force, along with friction [11].

The force output from the model is analysed for its accuracy in prediction of peak experimental device force. The elastoplastic behaviour of lead yields a hysteresis loop with numerous force values. The precision of the model in estimating the device forces is determined by comparing the nominal yield force obtained from the model against experimentally measured peak device forces. The peak force of the HF2V devices is the maximum force obtained during shaft displacement, shown in Fig. 3.

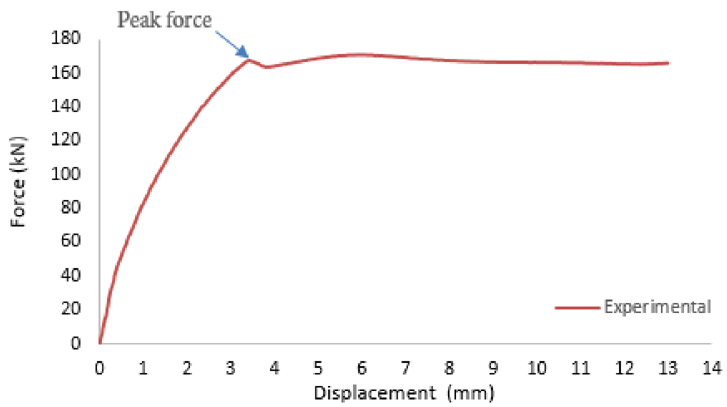

Fig. 3 – Force displacement plots of HF2V devices

In addition, comparison is also made relative to +/-14% standard error seen in testing 96 HF2V devices of 250kN force capacity, which is thus used as manufacturing variability to assess the results in context [7].

4. Results and Discussion

The simulations replicate the expected actual behaviour of lead in the lead extrusion damper under loading. The ALE meshing technique applied to the lead in the FE model enables the realistic simulation of lead flow around the bulge in the HF2V devices. The experimental peak forces are compared with the FE model forces and corresponding errors as shown in Eq. (1) are calculated and presented in Table 2. The peak experimental device force, the model device force, and the contact pressure forces and extrusion forces are included in the table.

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

Table 2 – Device data of 17 devices used for modelling

Device	F_{exp} (kN)	F_{model} (kN)	$F_{contact\ pr}$ (kN)	$F_{friction}$ (kN)	Error %
1.	160	167	54	106	4
2.	285	310	130	170	8
3.	390	400	135	265	3
4.	200	185	60	125	8
5.	346	345	145	190	0
6.	130	125	67	58	4
7.	150	152	78	74	1
8.	260	245	68	177	6
9.	155	155	45	110	0
10.	250	200	115	85	20
11.	170	175	27	148	3
12.	200	220	65	155	10
13.	260	245	45	140	6
14.	125	130	59	71	4
15.	190	213	70	150	12
16.	107	107	62	45	0
17.	520	650	265	385	20

The results in Table 2 show 14 out of 17 devices predict accurately, with less than 10% error, and there is 1 device with 12% error and 2 devices with 20% percent error. These results indicate the Finite Element modelling approach is promising as a potential tool for predicting forces for HF2V devices with an error range of 0%-20% [11]. The accuracy of force prediction match or exceed those in [11] for a simpler model.

The standard errors can be attributed to manufacturing variance and variability in experimental results [7], while the model does not have manufacturing or assembly variability. Thus, a perfect 1:1 match cannot be expected, but a spread shown in Fig. 4 should be expected due to real device variability. The spread accounts for variability in device force due to manufacturing variability by ± 1, 2, 3 SEs, represented by dotted lines. As seen in Fig. 2., 15 of 17 (88%) devices lie within ±1 SD of manufacturing variability of ±14 % and 2 devices (12%) lie under ±2 SE. Thus, all 17 devices are within ±2 SE of possible experimental variation in manufacture. These outcomes match, or slightly exceed, reasonable statistical expectations of being within the expected variability due to manufacture.

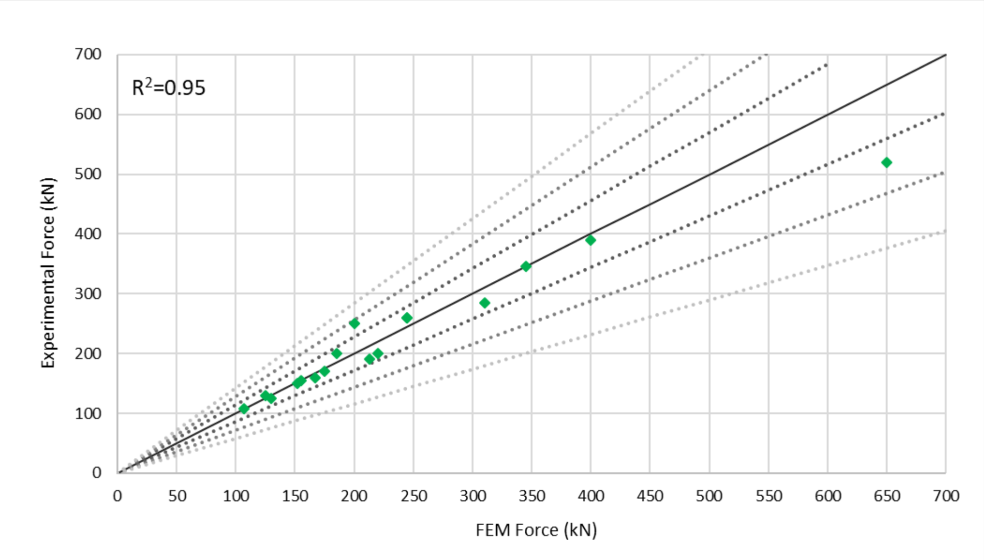

Fig. 4 - Standard Deviation representation of the devices. R^2=0.9**5** for the linear 1:1 line**.**

The FE modelling methods can be replicated because the same modelling parameters shown in Table 1 are applied for all the devices without any tuning or alterations to the modelling parameters. Only the device geometry was changed between simulations. Therefore, the modelling approach can be used to provide a good prediction for future device designs.

5. Conclusion

A novel Finite Element Modelling technique is created for modelling, analysis and visualization of operations of HF2V lead extrusion dampers, allowing ease of estimating device force capacities in the device design phase itself. The FE model is generic and can be used for modelling devices of varying force capacities with reasonable accuracy within a range of 0-20%. The device parameters can be modified to observe corresponding force changes in the HF2V devices and a design can be generated or modified to yield optimum force outputs required for a particular application. Therefore, it is a useful design tool to obtain the precise force capacity range of the desired device, limiting the need for extensive prototype validation and possible device redesign.

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