NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING
2019 Pacific Conference on Earthquake Engineering
TURNING HAZARD AWARENESS INTO RISK MITIGATION
4 – 6 April | SkyCity, Auckland | New Zealand

Finite Element Modelling of HF2V lead extrusion dampers for specific force capacities

V. Vishnupriya, G.W. Rodgers & J.G. Chase
University of Canterbury, Christchurch

ABSTRACT

High Force-to-Volume (HF2V) lead extrusion dampers can be used to protect structures by dissipating seismic response energy. The lead within the dampers deforms plastically by flowing around a bulged shaft, dissipating significant energy. This study develops a generic finite element modelling approach for these dampers to accurately predict device forces to optimize device designs for implementation into structures.

A 2D axisymmetric large-deformation finite element model with adaptive meshing is developed using ABAQUS. The model has a rigid shaft and deformable working material (lead). The total force output is the sum of the contact frictional forces and contact pressure forces acting between the moving shaft and the displaced lead in the devices. For validation, model results are compared to experimental data from 14 experimental devices of different sizes and force capacities.

The model predicts the force capacities of devices and simulates the stress distribution, and device behaviour with good overall accuracy. Model force-displacement plots exhibits good prediction capacity corresponding to experimental results. The error in predicted force capacity for 10 of the 14 modelled devices is less than 10%, with 3 further devices within 10%-20% errors and the one within 30% errors. Overall, a generic FEM modelling approach for highly nonlinear HF2V devices is developed, with very good performance compared to experimental data. This modelling approach enables improved optimization of device design for developing a specific design for buildings or bridges using these devices.

1 INTRODUCTION

It is important to protect structures using protective systems to reduce their seismic vulnerability. High Force-to-Volume Lead Extrusion Dampers (LED) are supplemental energy dissipation devices that enhance structural energy dissipation and reduce seismic structural response. The advantages of LEDs/HF2Vs have long been recognised and have been applied for improved damping systems (Latham et al., 2013; Rodgers, 2009, 2012; Skinner et al., 1980). Prediction of lead extrusion damper forces, stress, and force distribution are essential for device design. Few analytical models have been proposed to estimate the lead extrusion damper force capacities (Parulekar et al., 2004; Rodgers et al., 2007; Rodgers et al., 2006; Tsai et al., 2002; Vishnupriya et al., 2018).

Design based models that can precisely predict the HF2V force capacity are very limited (Vishnupriya et al., 2018). Currently, devices are manufactured and tested for determining the precise exact force capacities before application. Thus, there is a need for a more detailed methodology to better estimate the device force capacity in the design phase. Finite element (FE) analysis is an effective method for studying the nonlinear mechanics of device operations and computing the resulting force capacities and has not been used before as a damper force prediction tool (Jin and Altintas, 2012; Li et al., 2004).

1.1 HF2V lead extrusion damper

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. The HF2V device produces resistive forces when the device's shaft moves through the solid lead working material under seismic excitation or other loading. The lead is deformed plastically by the shaft bulge and displaced through the annular orifice between the bulge and the cylinder wall. The displaced lead moves behind the bulge towards the cylinder walls and end caps, producing large contact stresses. The lead quickly recrystallizes and regains its original properties, resulting in consistent device behaviour across multiple response cycles without any strain hardening or loss of strength or stiffness (Paul, 1940; Robinson, 1976). The total resistive forces developed in the HF2V devices is as a result of extrusion of lead and friction between lead-shaft and lead-cylinder surfaces.

1.2 Finite Element software

There are numerous different FE software packages available for simulations and analyses (ABAQUS-Users-Manual, 2013). However, ABAQUS is a popular FE tool for simulating complex contact problems, large deformation, nonlinear and dynamic problems like cutting and extrusion (Lei et al., 1999; Li et al., 2004; Nasr and Ammar, 2017). With accurate material properties and design dimensions of a device, it can be expected to realistically simulate the HF2V lead mechanics within a device, and thus estimate device resistive force capacity. A simple FEM model is developed which can be used as a reference design tool for predicting HF2V device force capacities.

2 METHODS

2.1 FE Model

A 2D axisymmetric model was created using ABAQUS/CAE as it is less computationally intensive than 3D models. (ABAQUS-Users-Manual, 2013). The modelling parameters of the FE model are as tabulated in Table 1 (Evans, 1970; Gondusky and Duffy, 1967; Lindholm, 1964; Loizou and Sims, 1953). Arbitrary Lagrangian–Eulerian (ALE) finite element method is used to simulate large deformation problems, allowing a moving mesh along with the moving part (Gadala and Wang, 2000; Zhao et al., 2012; Zhuang et al., 2008).

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 (Donea et al., 1982). 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.

Table 1: Device data used for modelling and analysis

Module	Model Parameter
Parts	- Analytical rigid shaft and wall and deformable lead
Material properties of lead	- Elastic properties: Young's Modulus (E) = 16 GPa, Poisson's Ratio (υ)= 0.44 and Density (ρ) = 11340 kg/m^3 - Plastic data: 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	- Dynamic Explicit - Step time = 1s
Interaction	- Kinematic friction
Contact	- Tangential friction. Friction coefficient = 0.25
Boundary Conditions	- Fixed end conditions at lead ends and cylinder wall - Displacement on shaft along Y direction - Velocity of 0.5mm/s at RP-1*
Meshing	- Element type : CAX4R/CAX3 - ALE meshing

*RP-1 – Reference points as shown in Figure 1.

An example device model geometry, showing the domain of the FE analysis and the associated boundary conditions is presented in Figure 1. The boundary conditions where the lead working material meets the device endcaps is considered as a fixed boundary. The steel cylinder wall that acts to confine the lead is modelled as a rigid boundary and a frictional interface is modelled between the lead and the cylinder wall.

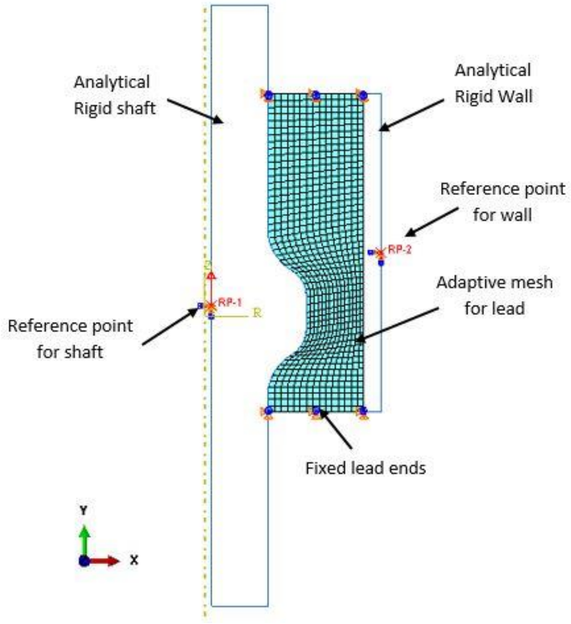

Figure 1: 2D Model parts and boundary conditions

2.2 HF2V device information

14 devices of different sizes and force capacities are considered for FE modelling (Vishnupriya et al., 2018). 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. F_{exp} indicates the experimental peak force attained from experiments, representing the force plateau during yielding at quasi-static test velocities. The devices are numbered in accordance to previous research and categorized as small (device 3), typical (devices 5-15) and large (devices 16-18) (Vishnupriya et al., 2018).

Table 2: Device data used for modelling and analysis

Device	F_{exp} (kN)	D_{cyl} (mm)	D_{blg} (mm)	D_{shaft} (mm)	L_{cyl} (mm)
3	55	17	13	12	56
5	160	89	40	30	110
6	280	89	50	30	110
7	360	89	58	30	110
8	200	66	40	30	130
9	346	66	50	30	130
10	130	50	32	20	50
11	150	50	32	20	70
13	260	60	42	33	160
14	155	50	35	24	100
15	250	70	48	30	75
16	145	54	35	30	160
17	200	54	36	30	160
18	260	190	45	140	27

2.3 Analysis

The force output from the model is analysed for its accuracy in prediction of experimental device behaviour. The total force obtained from the sum of extrusion forces and friction forces from the FEM model are compared with the experimental forces. The model's performance is initially assessed for its ability to replicate the lead flow in the HF2V devices with shaft displacement. Then, the developed model is validated against range of experimental results from devices with different designs, sizes, and different force and stroke capacities. The model will then be applied to investigate a wide range of device parameters, to enable further device optimisation and further delineate the force contributions of friction and extrusion to the overall resistive force produced by the device.

This computational approach will enable broader analysis of design parameters such as bulge size, shaft surface area, cylinder diameter, bulge length etc. Such parametric design studies can be undertaken on a much broader range of devices without the time and cost involved with experimentally testing every configuration.

3 RESULTS

The experimental forces are compared with the Finite element forces and corresponding errors as shown in Equation 1 are calculated and presented in Table 3. The experimental device force, the model device force, and the contributions from extrusion and friction are included in the table.

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

Table 3: Comparison of FE model forces to experimental forces

Device	F_{exp} (kN)	F_{model} (kN)	$F_{extrusion}$ (kN)	$F_{friction}$ (kN)	Error (%)
3	55	46	12	34	16
5	160	160	54	106	0
6	280	300	130	170	7
7	390	400	135	265	3
8	200	185	60	125	8
9	346	335	145	190	3
10	130	125	67	58	4
11	150	152	78	74	1
13	260	245	68	177	6
14	155	155	45	110	0
15	250	200	115	85	20
16	170	175	27	148	3
17	200	220	65	155	10
18	260	190	45	140	27

The results show that 11 out of 14 devices predict precisely with less than 10% errors, 2 devices within 20% percent errors and 1 *atypical* device with a large error of ~27%. The results indicate that the Finite Element modelling approach shows promise as a potential tool for predicting forces for *typical* devices with an error range of 0%-20%. The errors could be mitigated by better Finite Element modelling techniques, meshing and computation methods. However, the errors can also be attributed to manufacturing variance and variability in experimental results (Rodgers et al., 2019).

4 CONCLUSION

A novel Finite Element Modelling (FEM) technique is created for modelling and analysis of HF2V lead extrusion dampers. The FEM is generic and can be used for modelling all sizes and capacities of devices. The model predicts device force capacity with reasonable accuracy within a range of 0% - 20% for typical HF2V lead extrusion damper. Thus, the modelling approach presented shows promise as a reliable prediction methodology that can be a useful tool for the design of HF2V lead extrusion dampers. Ongoing research is investigating the influence of specific FE model assumptions and their influence on the predictive capability of the model.

5 ACKNOWLEDGMENTS

Partial funding for this research from the New Zealand Ministry of Business, Innovation and Employment (MBIE) through a Rutherford Discovery Fellowship, administered by the Royal Society Te Apārangi is gratefully acknowledged.

6 REFERENCES

ABAQUS. 2013. *User Manual*. Version 6.13-2. Dassault Systémes Simulia Corp., Providence, Rhode Island, USA.

Donea, J., Giuliani, S. & Halleux, J.-P., 1982. An arbitrary Lagrangian-Eulerian finite element method for transient dynamic fluid-structure interactions, *Computer methods in applied mechanics and engineering*, Vol 33 689-723.

Evans, J. 1970. Str*uctural analysis of shipping casks*. Vol. 8. Experimental study of the stress-strain properties of lead under specified impact conditions. Oak Ridge National Lab.

Gadala, M. & Wang, J., 2000. Elasto-plastic finite element simulation of rolling and compression between wedge-shaped dies, *Journal of Materials Processing Technology*, Vol 97 132-147.

Gondusky, J.M. & Duffy, J. 1967. *The Dynamic Stress-strain Relation of Lead and Its Dependence on Grain Structure*, Brown Univ Providence Ri Div Of Engineering.

Jin, X. & Altintas, Y. 2012. Prediction of micro-milling forces with finite element method, *Journal of Materials Processing Technology*, Vol 212 542-552.

Latham, D.A., Reay, A.M. & Pampanin, S. 2013. Kilmore Street Medical Centre: Application of an Advanced Flag-Shape Steel Rocking System, *New Zealand Society for Earthquake Engineering–NZSEE–Conference*, Wellington, pp. 26-28.

Lei, S., Shin, Y.C. & Incropera, F.P. 1999. Thermo-mechanical modeling of orthogonal machining process by finite element analysis, *International Journal of Machine Tools and Manufacture*, Vol 39 731-750.

Li, S., Bourke, M., Beyerlein, I., Alexander, D. & Clausen, B. 2004. Finite element analysis of the plastic deformation zone and working load in equal channel angular extrusion, *Materials Science and Engineering*, Vol 382 217-236.

Lindholm, U. 1964. Some experiments with the split hopkinson pressure bar, *Journal of the Mechanics and Physics of Solids*, Vol 12 317-335.

Loizou, N. & Sims, R. 1953. The yield stress of pure lead in compression, *Journal of the Mechanics and Physics of Solids*, Vol 1 234-243.

Nasr, M.N. & Ammar, M.M. 2017. An evaluation of different damage models when simulating the cutting process using FEM, *Procedia CIRP*, Vol 58 134-139.

Parulekar, Y.M., Reddy, G.R., Vaze, K.K. & Kushwaha, H.S. 2004. Lead Extrusion Dampers for Reducing Seismic Response of Coolant Channel Assembly, *Nuclear Engineering and Design*, Vol 227 175-183.

Paul, A. 1940. Recrystallization of lead, *Transactions*, Vol 137, 222.

Robinson, W.H. & Greenbank, L.R. 1976. An Extrusion Energy Absorber Suitable for the Protection of Structures During an Earthquake, *Earthquake Engineering & Structural Dynamics*, Vol 4 251-259.

Rodgers, G.W. 2009. *Next Generation Structural Technologies: Implementing High Force-to-Volume Energy Absorbers*, Mechanical Engineering. University of Canterbury, Christchurch, New Zealand.

Rodgers, G.W., Chase, J.G. & Mander, J.B. 2019. Repeatability and High-Speed Validation of Supplemental Lead-Extrusion Energy Dissipation Devices, *Advances in Civil Engineering 2019*.

Rodgers, G.W., Chase, J.G., Mander, J.B., Leach, N.C. & Denmead, C.S. 2007. Experimental Development, Tradeoff Analysis and Design Implementation of High Force-to-Volume Damping Technology, *Bulletin of the New Zealand Society for Earthquake Engineering 2007*, Vol 40 35-48.

Rodgers, G.W., Chase, J.G., Mander, J.B., Leach, N.C., Denmead, C.S., Cleeve, L. & Heaton, D. 2006. High Force-to-Volume Extrusion Dampers and Shock Absorbers for Civil Infrastructure, *Proceedings of 19th Australasian Conference on the Mechanics of Structures and Materials*.

Rodgers, G.W., Solberg, K.M., Mander J.B., Chase, J.G., Bradley, B.A. & Dhakal, R.P. 2012. High-Force-to-Volume Seismic Dissipators Embedded in a Jointed Precast Concrete Frame, *Journal of Structural Engineering*, Vol 138 375-386.

Skinner, R., Tyler, R., Heine, A. & Robinson, W. 1980. Hysteretic dampers for the protection of structures from earthquakes, *Bulletin of the New Zealand National Society for Earthquake Engineering*, Vol 13 22-36.

Tsai, C.S., Lai, W.S., Chang, C.W. & Li, M.C. 2002. Testing and Analysis of a New Lead-Extrusion Damper, ASME 2002 Pressure Vessels and Piping Conference, *American Society of Mechanical Engineers*, 215-220.

Vishnupriya, Rodgers, G.W., Mander, J.B. & Chase, J.G. 2018. Precision Design Modelling of HF2V Devices, *Structures*, Vol 14 243-250.

Zhao, H., Wang, H.-N., Wang, M.-J. & Li, G.-J. 2012. Simulation of extrusion process of complicated aluminium profile and die trial, *Transactions of Nonferrous Metals Society of China*, Vol 22 1732-1737.

Zhuang, X.-C., Zhao, Z., Xiang, H. & Li, C.-X. 2008. Simulation of sheet metal extrusion processes with Arbitrary Lagrangian-Eulerian method, *Transactions of Nonferrous Metals Society of China*, Vol 18 1172-1176.