Finite Element Modelling (FEM) of the Asymmetric Friction Connection (AFC) with Belleville Springs (BeSs): challenges and ongoing developments

F. Alizadeh & S. Ramhormozian

Department of Built Environment Engineering, Auckland University of Technology, Auckland.

G.C. Clifton

Department of Civil and Environmental Engineering, University of Auckland, Auckland.

ABSTRACT

The Sliding Hinge Joint (SHJ) is a low-damage beam-column connection used in steel moment-resisting frames. It allows large beam-column rotation to occur with minimal damage, through sliding in asymmetric friction connections (AFCs) that are located at the web bottom bolt and bottom flange levels. AFC is friction seismic energy dissipating component of the SHJ. Following a set of experiments and different analytical research carried out on the Asymmetric Friction Connection, modifications to improve the performance of the AFC have been proposed, especially in terms of reducing the post-earthquake loss of strength and stiffness. A significant modification has been using partially deflected Belleville Springs (BeS) designed and manufactured to fit the purpose. This paper delves into the presentation of an ongoing finite element modelling for the components of the AFC, using ABAQUS. It outlines the progress made to date and discusses the challenges encountered, addressed, and overcome. These include adaptation and adjustment of material properties for various steel types, attempts to model threaded and nonthreaded bolts as well as BeS and complexities and computational demands associated with such approaches.

1 INTRODUCTION

1.1 Background

In the event of a major earthquake, including the ultimate limit state (ULS) and larger earthquakes, the building experiences a substantial amount of energy imposed on it due to its dynamic response to the ground excitation. The way this energy is dissipated within the structure plays a pivotal role in determining the extent of structural damage incurred. While it is impractical to design structures that are completely damageresistant against all conceivable earthquakes, it is feasible to enhance traditional design and construction methods with the aim of reducing the likelihood and severity of structural and non-structural damage during major earthquakes and to elevate the structural damage threshold as much as possible.

Recognizing the high cost of designing and constructing structures to remain in the elastic range of structural materials under severe earthquakes, building codes acknowledge the need for an approach to allow inelasticity to occur in severe events e.g. through ductile design. Moreover, stiffer structures, designed to remain elastic, with lower natural period, might adversely respond to specific ground excitations, leading to increased non-structural and contents damage. Current building codes emphasize the paramount importance of satisfying the life safety mandate. However, this implies that in events more severe than the design level, structural damage is anticipated in even well-designed and detailed buildings, necessitating repairs or, in some cases, demolition. This scenario imposes substantial costs and disruptions on affected communities and carries a significant environmental burden. To address this critical issue, there has been ongoing development in low-damage design and construction methodologies.

1.2 The low-damage design philosophy

In the seismic design of structures, the ductile design concept allows structural designers to undertake a cost-effective design by incorporating post-elastic capacity of the structure. This means the energy is allowed to be dissipated through inelastic deformations of the structural members. However, this is associated with permanent damage. The repair of the damage may be significantly costly and/or not practical [1]. To avoid these undesirable economic effects of earthquakes, following recent several damaging events, the global tendency has been moving towards the development and implementation of low damage seismic resisting systems.

Two of the initial key motivations for the low damage design philosophy developments were the similar experiences in the 1994 Northridge [2] and the 1995 Kobe [3] earthquakes, in which significant unexpected damage to the welded connections of multi-story, moment-resisting steel-framed buildings were observed [4].

The low damage design philosophy aims, in addition to satisfying the well-accepted “life safety” mandate, to minimize the economic losses due to post-earthquake damage repair as well as downtime. The importance of this has again been illustrated in further major earthquakes such as the 2010/2011 Canterbury earthquake series, the 2010 Maule earthquake, and the 2016 Kaikoura earthquake [5]. These recent earthquakes have clearly demonstrated that conventional construction, even in technologically advanced countries with well-designed and detailed structures, is not immune to significant earthquake damage [5, 6].

1.2.1 The Sliding Hinge Joint

An example of a low-damage system developed for seismic moment-resisting steel frames (MRSFs), one of the most commonly used lateral force resisting systems, is the Sliding Hinge Joint connection (SHJ) with Asymmetric Friction Connections (AFCs) as shown in Figure 1. The AFCs are energy dissipating components of the SHJ.

The SHJ, proposed by Clifton [7] and shown in figure 1, adopted the concept of pinning the beam to the column at the top flange, utilizing the AFC at the bottom flange and bottom web level.

The AFC in the SHJ as shown in the figure 2, consists of five plies, including the beam bottom flange, bottom flange plate (cleat), cap plate, and two shims at both sides of the cleat, all clamped by the pre-tensioned high strength friction grip (HSFG) structural bolts. The AFC has two main sliding surfaces on both sides of the cleat.

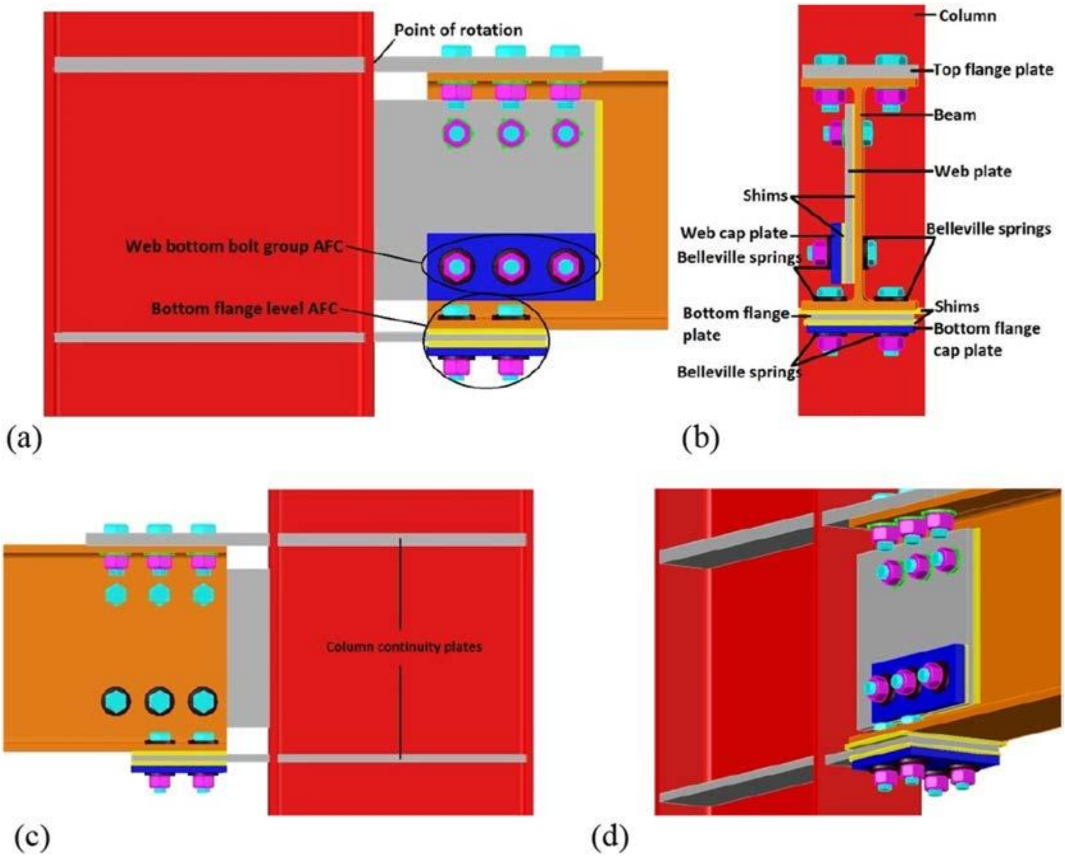


Figure 1: The sliding hinge joint (SHJ) views (a) front (b) beam cross sectional, (c) back, and (d) 3D [6]

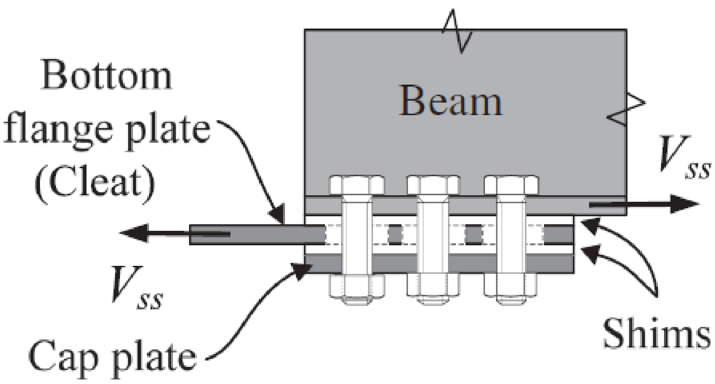


Figure 2: The AFC at the bottom flange level [8]

1.2.2 The Optimised Sliding Hinge Joint

Ramhormozian et al.[9, 10] showed that using partially deflected Belleville Springs (BeSs) with sufficient axial deformation to reach the installed bolt tension in the elastic range, being installed at both head and nut sides of the AFC bolts, would reduce the post-sliding clamping force loss, improve the self-centering capability, increase the system coefficient of friction, reduce the additional imposed tension on the AFC bolts during stable sliding due to prying actions and/or moment, shear, and axial force (MVP) interactions, and reduce the severity of the sliding surfaces' wearing. BeSs, as shown in figure 3, are truncated conical washer-type elements of very high strength steel that compress elastically, if they are pre-set, to a flat disk under a closely defined level of force. The enhanced version of the SHJ [10] has been called Optimised Sliding Hinge Joint (OSHJ) [11]. The AFCs of the OSHJ are called Optimised Asymmetric Friction Connection (OAFC) in this paper.

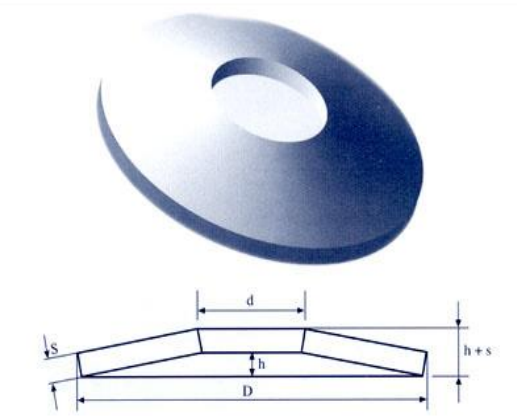


Fig. 3. A typical Belleville spring design [12]

The OAFCs bolts, as mentioned before, are tightened in the elastic range and effectively remain elastic during seismic induced sliding, retaining most of their installed bolt tension after significant sliding [11].

2 FINITE ELEMENT ANALYSIS

Finite element analysis (FEA) is a powerful and useful tool for engineering researchers to create a virtual testing programme. The aim of undertaking the FEA study is to simulate, as closely as practicable, the experimental behaviour and then to monitor and analyse important parameters such as forces and stress distribution.

The OAFC initial models were created using dimensions close those of the past experiments and the obtained results were promising [13]. To ensure the accuracy of these models, it is crucial to refine the model and accurately simulate its components. Therefore, the focus is on modelling specific components such as bolts and BeS as detailed as possible. The subsequent sections outline the details of the proposed and implemented modelling approach. This includes reporting the challenges faced in the modelling process along with the solutions implemented.

In this study, ABAQUS/CAE v2024/standard software [14], as one of the well-established nonlinear finite element analysis packages, is used for modelling and analysing the samples. The software has the ability to take into account both material and geometrical nonlinearities as well as contact interactions and bolt loads.

2.1 Material

It is essential to accurately define the true-stress data points of all types of materials used in any finite element model. This includes the true stress strain in the elastic as well as in the plastic range. Moreover, given the focus of this study is on seismic behavior, the connection assembly undergoes cyclic loadings. As for the true stress-strain data points, instead of experimentally testing different types of steel used in the OAFC components, in this research experimental data from steel grades 300 [15], 700, 960 [16], and grade 10.9 bolt [17, 18] along with the data provided by the supplier for the bolts of grade 8.8 [19], were utilized and inter/extrapolated to obtain the required true stress-strain data, as shown in Figures 4 and 5.

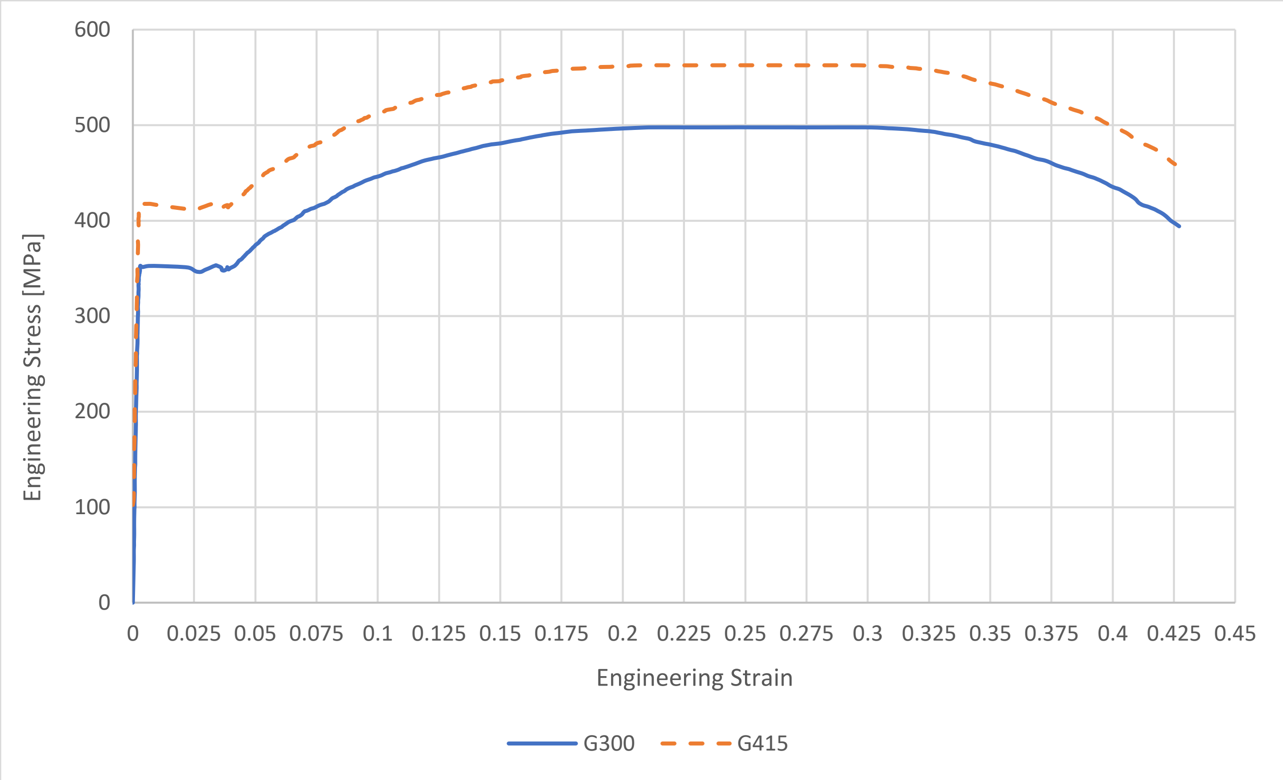


Fig. 4. Stress-strain curves for Grades 300 and 415 steel.

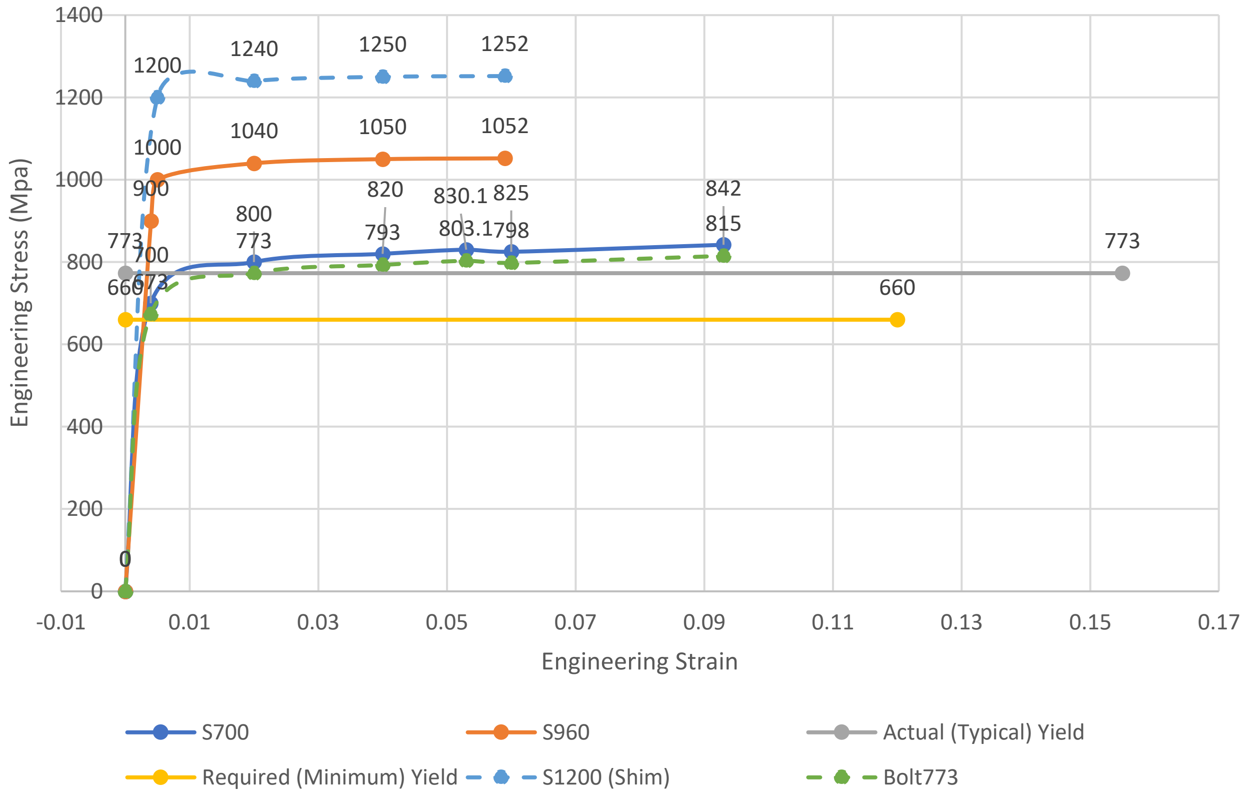


Fig. 5. Stress-strain curves for bolts and shims.

2.2 Modelled specimen

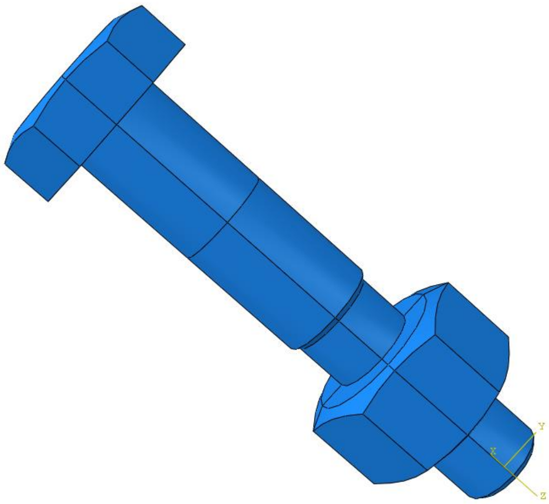
It has been demonstrated experimentally and analytically that the clamping force of the AFC degrades after a few sliding cycles, leading to a reduction in bolt tension[6, 9, 10] . Developments of the OSHJ resulted in proposing the use of well-designed and detailed partially deflected BeSs with bolts installed in the elastic range, instead of the initial method of bolt tightening proposed by Clifton [7] of fully tensioning bolts in absence of BeSs. Improved seismic performance has been observed in experiments utilizing Belleville springs (BeSs) [10]. To undertake an extensive parametric study on different configurations and capacities of the OAFCs, it is crucial to create appropriate Finite Element Models of the OAFC and thoroughly investigate the behaviour of the OAFC and its components such as HSFG bolts and BeSs.

2.2.1 Bolt model

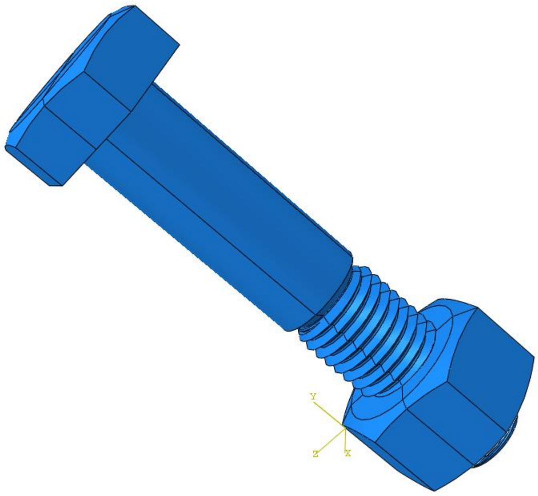
The bolts are first to be modelled individually, to validate the modelling techniques and paraments, ensuring their axial behaviour, e.g. stiffness, is captured accurately, before assembling in the OAFC. Two variations of bolt with nut assemblies were simulated, one with threads and the other without. The former eliminated the threads to streamline the model and minimize computational expenses (see Fig. 4.a), while the latter (Fig. 4.b) closely replicated the components tested in experiments as outlined in [9, 10].

Initially, a surface load was applied simultaneously to the bottom surface of the bolt head and the upper surface of the nut, and subsequently the bolt's behavior (e.g. axial load and deformation) observed and recorded.

The findings revealed that the threaded bolt model demonstrated around 10% improvement in accuracy compared to the non-threaded bolt model, when they were compared with analytical models proposed by[6] . However, it's important to note that the computational time for the two models is not comparable; the non-threaded bolt model runs approximately more than ten times faster, as documented in the study.



(a)



(b)

Fig. 6. Bolt modelling. a) dumbbell bolt, b) Real bolt.

2.2.2 Belleville Spring model

To assess the correctness of modelling technique and axial behavior of Belleville springs (BeS), they were assembled on a plate, and displacement was applied to be compared with the BeSs supplier’s testing data for validation purposes. A cyclic displacement-based loading regime, including three full cycles, were applied on the upper BeS edge. Subsequently, the load-deflection characteristics were recorded and compared with those provided by the supplier. The BeS was simulated using both solid elements for the entire model and shell elements with finer mesh for a quarter of the model to expedite the analysis process and reduce computational time. The BeS was initially represented using solid elements; however, due to the presence of a curve along the edge of the BeS, it was opted to employ continuum shell element modelling. Continuum Shell elements are used to model structures in which one dimension, the thickness, is significantly smaller than the other dimensions. The comparison of the results and available experimental data is currently underway.

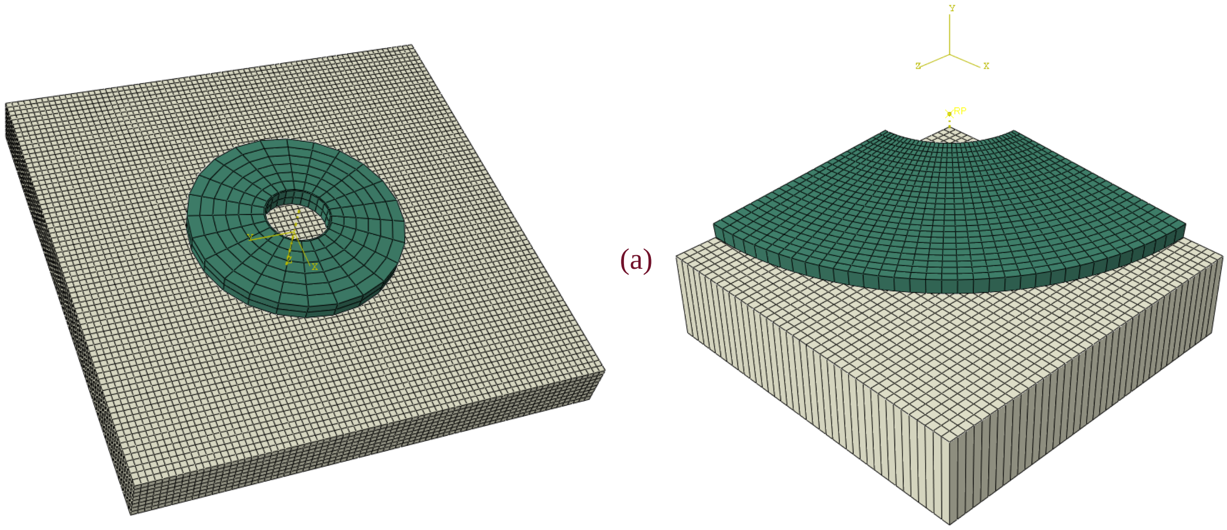


Fig. 7. Belleville spring modelling. a) Solid element, b) Shell continuum element.

3 CONCLUSIONS

The Finite-element modelling and analysis serve as a cost-effective and efficient tool to complement experimental investigations in engineering systems. However, ensuring the creation of accurate models for realistic system behavior requires a careful approach of modelling and analysis to prevent common issues dealing with convergence, accuracy, and computational costs. This paper explores the utilization of ABAQUS software for numerically analyzing the behavior of Optimized Asymmetric Friction Connection components. The aim is to optimize modelling approach and parameters, considering detailed time-consuming simulations requiring high accuracy are expected.

A convergence study was conducted on two distinct bolt shapes and two different Belleville spring (BeS) element types. The results indicated a sensitivity to bolt shape. Furthermore, the selection of an appropriate element type, aligned with simulation objectives, was crucial for obtaining accurate results. Two potentially ideal elements were employed. Moreover, a thorough literature review and manipulation were conducted to identify suitable plastic materials. The presented numerical results demonstrate promising agreement with experimental findings [7, 10] and analytical results.

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