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FINITE ELEMENT MODELLING OF DETACHABLE SHORT LINKS

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Abstract. *Eccentrically braced frames with replaceable links are viable seismic resisting systems that guarantee large dissipative capacity and quick and easy replacement of the damaged dissipative zones after seismic events, thus reducing the repair costs. Experimental tests carried out within DUAREM research project [12] demonstrated the high effectiveness of this system and highlighted the importance of the bolted connections of the shear links on the system response at both global and local level. In order to investigate the behaviour of the tested detachable links, finite element analyses have been carried out. The finite element (FE) models are calibrated on the basis of the experimental response curves in terms of the shear force and link rotation. Once calibrated the finite element models, several parameters have been investigated such as the type of pre-loadable bolts (i.e. HR and HV), the level of bolt clamping force, the boundary conditions, the presence of constructional tolerances (e.g. initial gap between end-plate at both link ends). The results from the parametric study enables the characterization of the shear and axial force interaction on the link end connections.*

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1 INTRODUCTION

Eccentrically braced frames (EBF) are widely used in steel structures in seismic areas because they combine high lateral stiffness with large ductility and dissipative capacity. The former is mostly guaranteed by the braces, while the latter by the links that behave as dissipative fuses. In particular, short links (i.e. that mostly dissipate energy by shear yielding) provide the better response in terms of resistance, stiffness and ductility [1-11]. However, in split-K and D configurations of EBFs the concentration of damage into the links can lead to high repair costs due to the interference of the slab and the beam containing the links. In order to overcome this problem, recent studies [12-21] investigated the possibility to use detachable links for both new and existing structures to allow quick removal of damaged links and easy repair of the structure after earthquake.

The reparability after earthquake improves if the residual interstorey drifts are small (e.g. similar magnitude of the out-of-plumb constructional tolerances). This consideration implies that structures equipped with fuses, as shear links, should have sufficient re-centering capability to limit the residual lateral displacements. EBFs are poorly redundant systems with limited re-centering capability if they are alone, but as dual system (i.e. combined with flexible and elastic moment resisting frames) it is possible to restore the building after seismic damage occurred.

The results of Duarem project [12] clearly demonstrated that dual-eccentrically braced frame (D-EBF) with replaceable links preserve the benefits of the EBFs with satisfactory re-centering capability allowing the easy repair of the structure after seismically induced damage.

A crucial aspect influencing the behaviour of detachable links is the design of the bolted connections at both link ends, which should resist the maxima forces developed by the link. Short links with axial restraints, as the typical case of detachable links, can develop both shear overstrength (i.e. the ratio between the peak shear force V_u and plastic shear strength V_p) larger than the 1.5, which is the value currently recommended by EC8 [25], and axial tensile forces [22, 23] that are not accounted for by EC8 [25]. In order to investigate this aspect, the results of parametric finite element analyses are described and discussed in this paper. The accuracy of the numerical models was first validated on the basis of the experimental tests carried out by [12]. Afterwards, the study was extended by investigating the following parameters: i) the boundary conditions of the links, ii) the type of high strength bolts, iii) the clamping force of bolts and iv) the constructional tolerances.

2 FINITE ELEMENT MODELLING

The numerical models were developed in Abaqus 6.14 [24]. The geometrical and mechanical features of the examined links are those of the all-steel detachable links with flush end-plate connections and slab disconnected from the EBF, that were tested in the DUAREM research project [12], see Figure 1. The shapes of links of the DUAREM mock-up and analysed hereinafter, are the following: i) L1 corresponds to the link assemblies on the 1st (S1) and 2nd (S2) floor; ii) L2 corresponds to the link assembly of the 3rd floor (S3) (see Figure 1).

The elastic flexural stiffness of both the end connections and the links are reported in Table 1, where it is also shown the normalized length of the link e/e_s (being e the link length and e_s the limit length for shear links).

Assembly	$S_{j,ini}$	K_{link}	$S_{j,ini}/K_{link}$	e/e_s
L1	5.43E+10	3.26E+10	1.7	0.43
L2	5.43E+10	2.23E+10	2.4	0.31

Table 1 Initial stiffness of the joint and flexural stiffness of the link

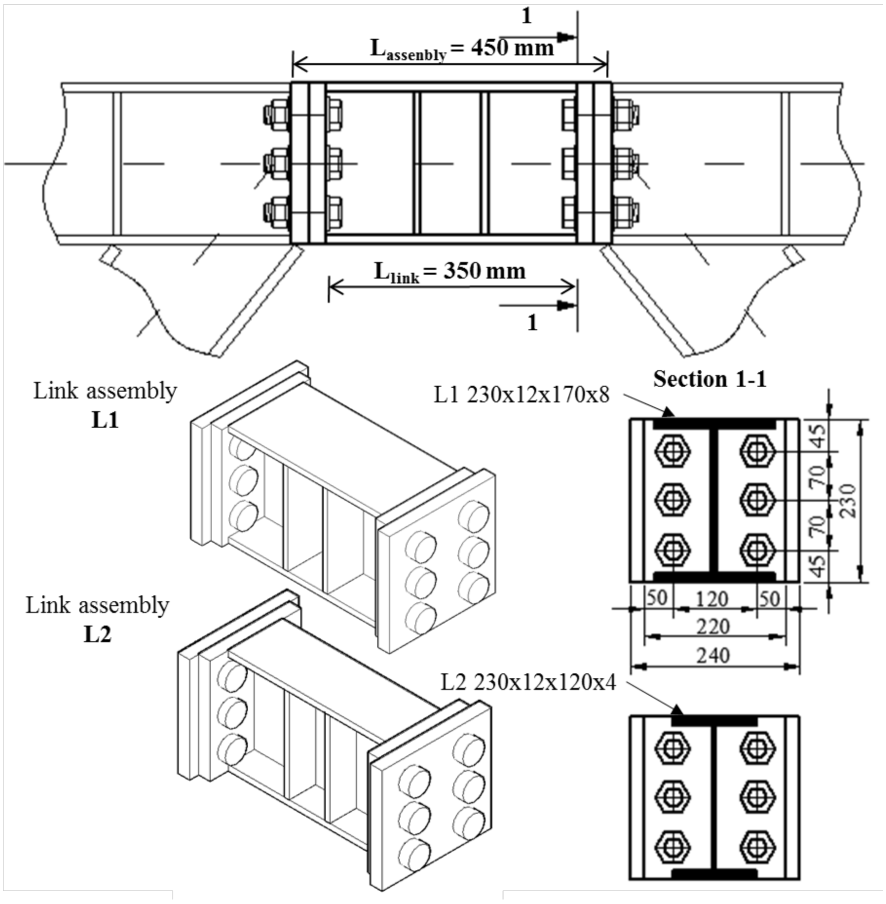


Figure 1 Shapes of the examined links

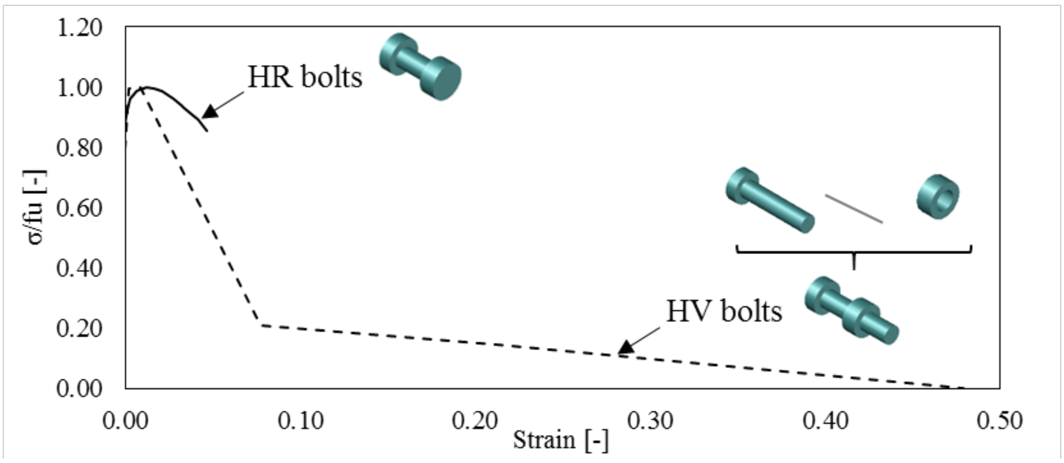


Figure 2 Bolt material modelling

The stress-strain curves of the steel parts were obtained from those experimentally measured within DUAREM project [12]. Yielding was modelled by means of the von Mises yield criteria. Plastic hardening was represented using a combined isotropic and kinematic hardening. The "Ductile damage" option was considered in order to account for the material degradation.

The mechanical properties of both HR and HV bolts were modelled according to [26]. In particular, HR bolts were modelled as a single part, with the stress-strain curve depicted in Figure 2, but the stiffness and strength were adjusted in order to account for the nominal diameter of the bolts assumed for the geometry. This was achieved by reducing the material strength with a value corresponding to the A_{nom}/A_s (nominal area divided by the tensile bolt area) ratio and the evaluation of the bolt stiffness based on the method proposed by [27].

The HV bolt assemblies were modelled as shown in Figure 2. In this case, the assembly is composed of 3 parts: the bolt (i.e. shank+head), the wire element and the nut, each one fulfilling a particular role. The solid parts (bolt and nut) have the role to transfer the shear forces that occur at the connection level, while the wire will transfer the tensile forces from the bolt head to the nut. In particular, the wire is characterized by a non-linear force-displacement response defined as given by [26] and shown in Figure 2.

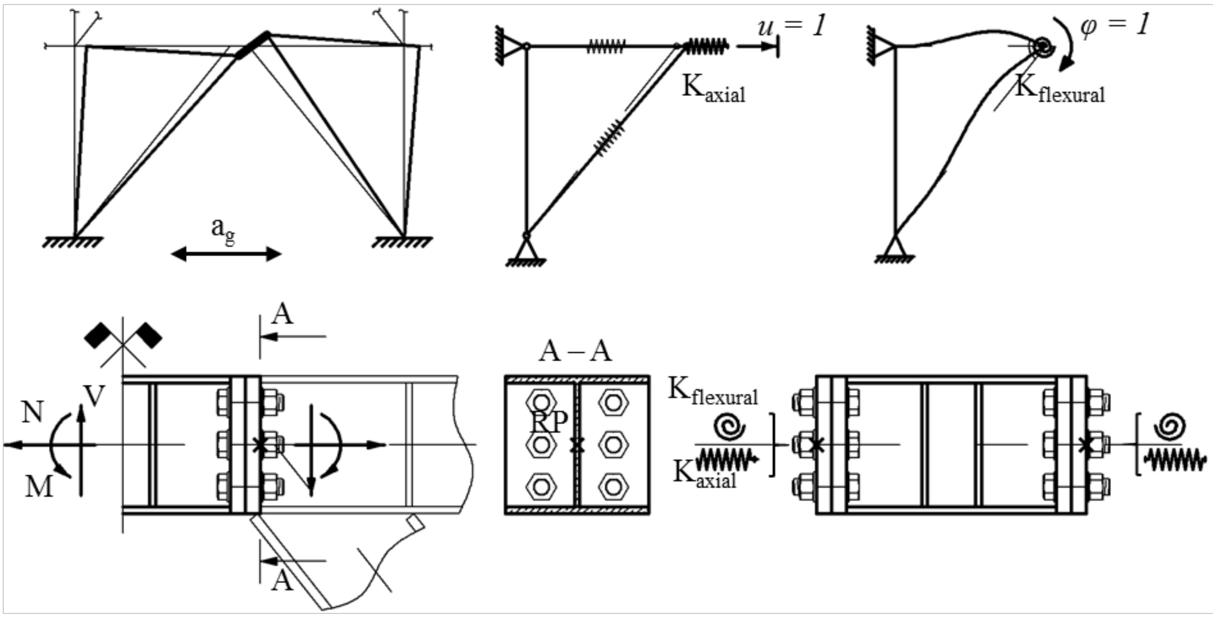


Figure 3 Evaluation and modelling of the frame flexural and axial stiffness

The interactions needed for the model were defined considering the "Hard contact" option for the normal direction and "Coulomb friction" model with 0.3 penalty coefficient for the tangential behaviour. The welds at different plate junctions were modelled with "Tie" constraints.

The presence of the frame (i.e. beam segment, braces and column) connected to the links were simulated with two equivalent mechanical springs, namely one accounting for the flexural deformability and another for axial deformability. The stiffness of the frame was obtained based on the sub-structuring in Figure 3. The boundary conditions were assigned to reference points (RP) that are located at the ends of the link-connection assemblies as shown in Figure 3.

A structured meshing strategy was adopted for the entire model. The solid parts of the model were meshed using C3D8R (8-node linear brick, reduced integration) elements, while for the wire element of the HV bolt assemblies, B31 (2-node linear beam in space) elements were used.

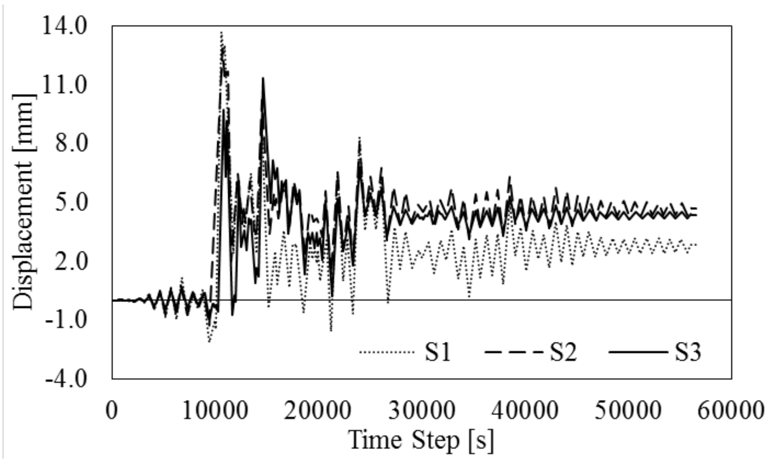


Figure 4 Displacement time histories for FE model validation

In order to simulate as closely as possible the test conditions, the experimental displacement time histories were applied at both assembly ends (see Figure 4). Dynamic Implicit quasi-static analyses were carried out. The comparison between the simulated and the experimental response curves is depicted in Figure 5 a, c and e, which clearly shows a satisfactory accuracy.

3 PARAMETRIC ANALYSES

3.1 Investigated parameters

The parameters considered in the presented study were the following:

- The type of high strength preloadable bolt assemblies: HR or HV.
- The boundary conditions, namely (i) fully restrained at both ends (FR), (ii) deformable restraints modelling axial and flexural stiffness of the frame (DR) and (iii) fully restrained conditions with axial release at one end (FR-Ax).
- The level of bolt clamping force, namely (i) F_p that is the design value recommended by EC3 1-8 [28] and showed in *Eq. (1)*, (ii) 50%F_p and (iii) $F_{p,max}$ (the maximum preloading force defined as well in *Eq. (1)*.

$$
\begin{aligned}
F_p &= 0.7 f_{y,b} A_s \\
F_{p,\max} &= f_{y,b} A_s
\end{aligned}
\tag{1}
$$

Where $f_{y,b}$ is the yield stress of the bolt and A_s the resisting area of the shank.

- The presence of constructional tolerances – an initial gap between the frame and the link is considered as follows: 0.5 and 1 mm on each side for L1 assembly and 0.25 and 0.5 mm for L2 assembly. Additionally, in order to account for the influence of two different surface treatments of the end-plates, two friction coefficients μ were considered (i.e. 0.3 and 0.5).

S1

S2

S3

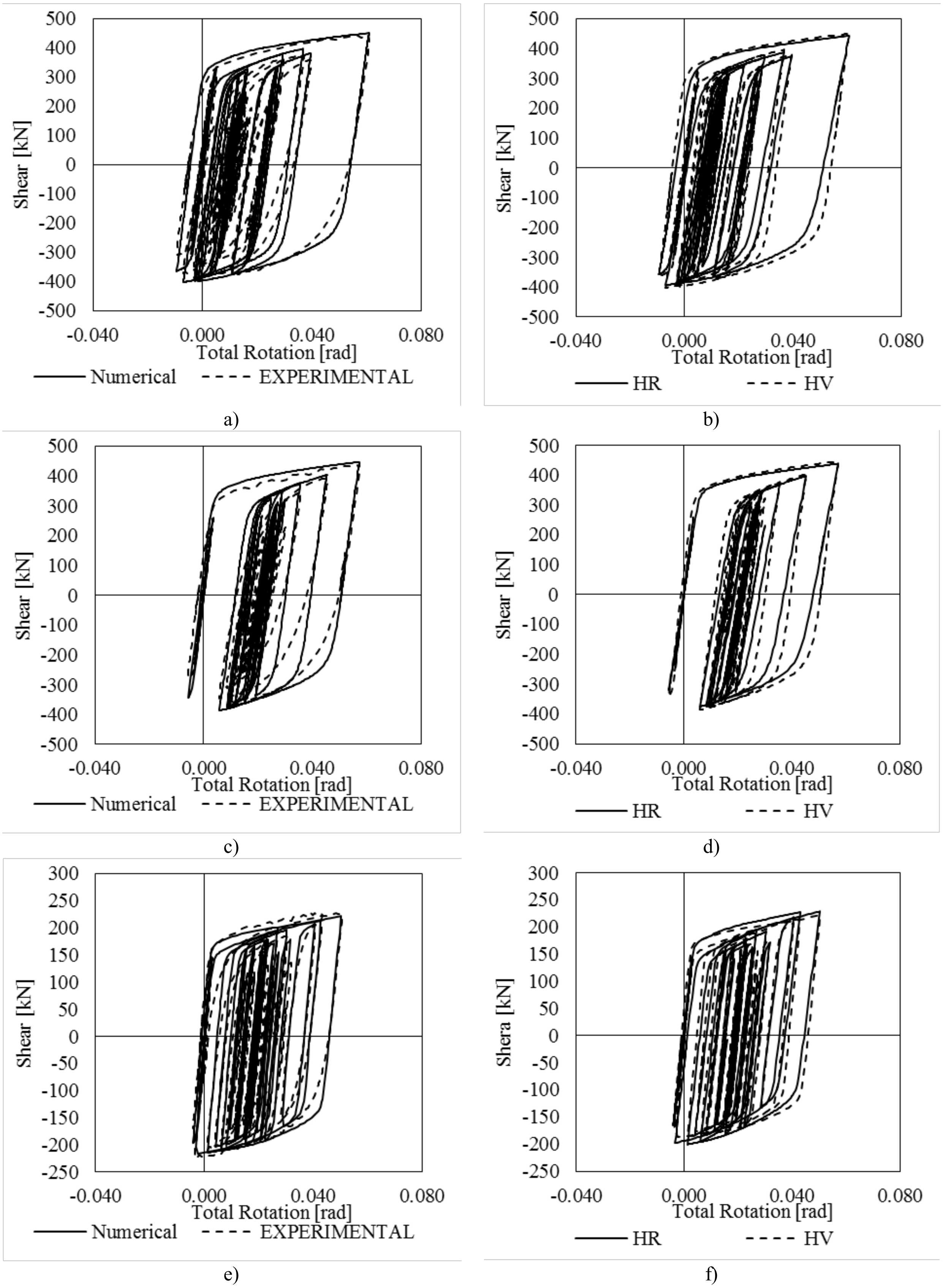
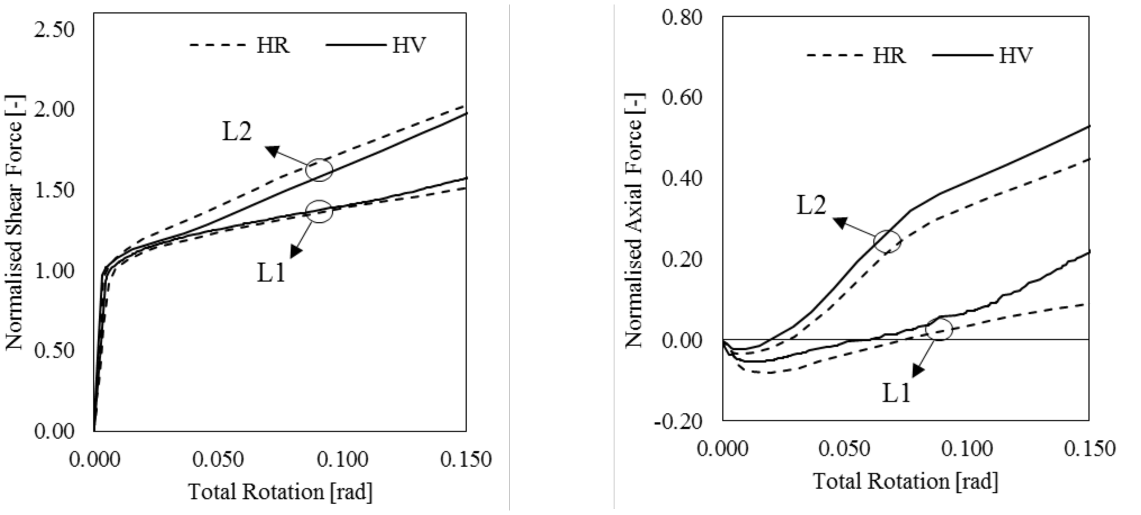


Figure 5 Cyclic response of the 3 link assemblies. Experimental and numerical comparison and the HR and HV numerical models comparison.

3.2 Type of high strength bolts

The main difference between HR and HV bolts is the failure mode. As shown by [26], HR bolts have a failure characterized by the necking of the shank, while HV fasteners fail by nut stripping. The influence of bolt assembly was investigated for cases with deformable and full rigid restraints. However, for brevity sake, only the cases with deformable restraints are depicted in Figure 5 and Figure 6. As it can be noted, in the examined cases the type of bolt does not appreciably affect the stiffness, yielding shear force or the hardening behaviour of the link (see Figure 5 b, d and f). This result is consistent with the observed failure mode of the links, where no appreciable plastic engagement of the bolts was recognized.



a) Shear overstrength V/V_p b) Normalized axial force $N/N_{pl,fl}$

Figure 6 Monotonic analysis of models with deformable restraints

Some slight differences can be observed in terms of axial forces developed by the two link assemblies. Indeed, as depicted in the plots of Figure 6 where the ratios between the axial force N and the plastic strength of the two flanges $N_{pl,fl}$ are reported, the links with HR bolts exhibit larger tensile forces than those of the corresponding assemblies with HV bolts. This result depends on the stiffness of the connection, which is slightly larger in non-linear range when HR bolts are adopted. Anyway, considering that this difference is negligible, the numerical analyses discussed hereinafter were carried out using HR bolts.

3.3 Boundary conditions

The boundary conditions do not appreciably affect the response of the links L1 in terms of stiffness and yield shear force, as shown in Figure 7a. However, for the L2 links the presence of axial restraints induces significantly large hardening (i.e. larger shear overstrength V/V_p), as depicted in Figure 7b. The different response of L1 and L2 depends on the tensile axial forces developed by the two assemblies. Indeed, the catenary actions developed in L1 are almost the same for DR and FR boundary conditions, see Figure 7c. On the contrary, Figure 7d shows that boundary conditions modify the tensile forces developed in L2, being obviously larger in FR case. The difference between L1 and L2 depends on the actual link length. Indeed, the e/e_s ratio is larger for L1 assemblies than for L2. Indeed, the effects of geometrical non-linearity are more significant for the shorter links [22, 23]. It is trivial to observe that the cases with free axial deformation cannot exhibit any axial force.

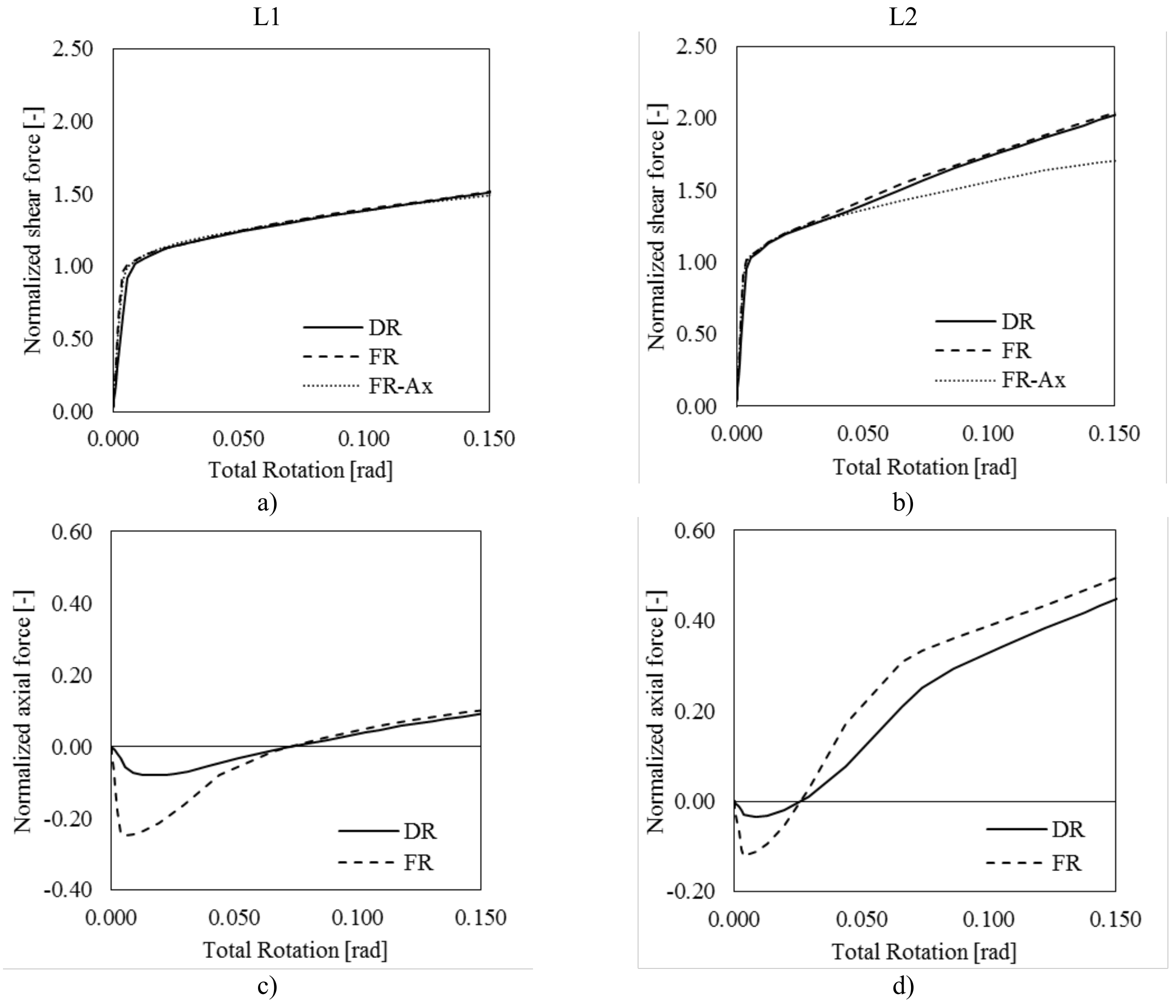


Figure 7 Influence of boundary conditions on the shear and axial force for link assemblies

3.4 Clamping force level

Figure 8 a and b show the results of the analyses on L1 and L2 assemblies at the variation of the clamping force of the bolts. The results presented correspond to models with HR bolts and deformable restraints (DR). As it can be observed, the bolt pretension force does not influence the shear overstrength of the links, either in terms of strength or stiffness.

For what concerns the axial forces developed in the links, Figure 8 c and d show the cases with the lower clamping force (i.e. 50% F_p) exhibit the larger compressive arching-like forces in the initial phase, owing to the larger deformability of the connection. As expected, higher clamping forces lead to lower extensional deformability of the connection and, consequently, higher tensile axial forces. However, at large rotation demands this effect is lost because the influence of clamping force extinguishes.

3.5 Constructional tolerances and superficial treatment of the connection's end-plates

In real cases, the perfect conditions assumed in numerical modelling are usually not met. Therefore, it was investigated the behaviour of the link-connection assembly, with HR bolts and considering fully restrained conditions, when gaps between the link and the frame are present. In addition, the influence of different surface treatments of the end-plates in contact were examined.

Figure 9 a and b depict the comparison of the monotonic curves in terms of normalized shear force up to rotation equal to 0.15 radians. It can be noted that the shear capacity is scarcely influenced by the constructional tolerances as well as the type of superficial treatments. Even the stiffness of the assembly is moderately affected (Figure 9 c and d), but slip phenomena are observable for the smaller friction coefficient value (i.e. $\mu = 0.3$). This finding can be explained by the level of pre-tension force that is applied to the bolts when the gap increases. Indeed, to close this gap the bolts are tightened reaching forces larger than their yielding resistance. When this event occurs the bolts loose axial stiffness and the pre-tensioning of the plates reduces. Consequently, combined with low friction coefficient, slippage become more evident. The relative sliding of the end-plates is not observed for the models with a friction coefficient of 0.5.

The smaller shear overstrength values observed for all models, compared with the no gap one, can be explained by the larger tensile force developed in the link. Indeed, as observable from Figure 9 e and f, the level of tensile force in the link is the largest at beginning, reaching values up to the axial plastic capacity of the link flanges ($N_{\mathrm{pl,fl}}$), but it decreases when the link rotates.

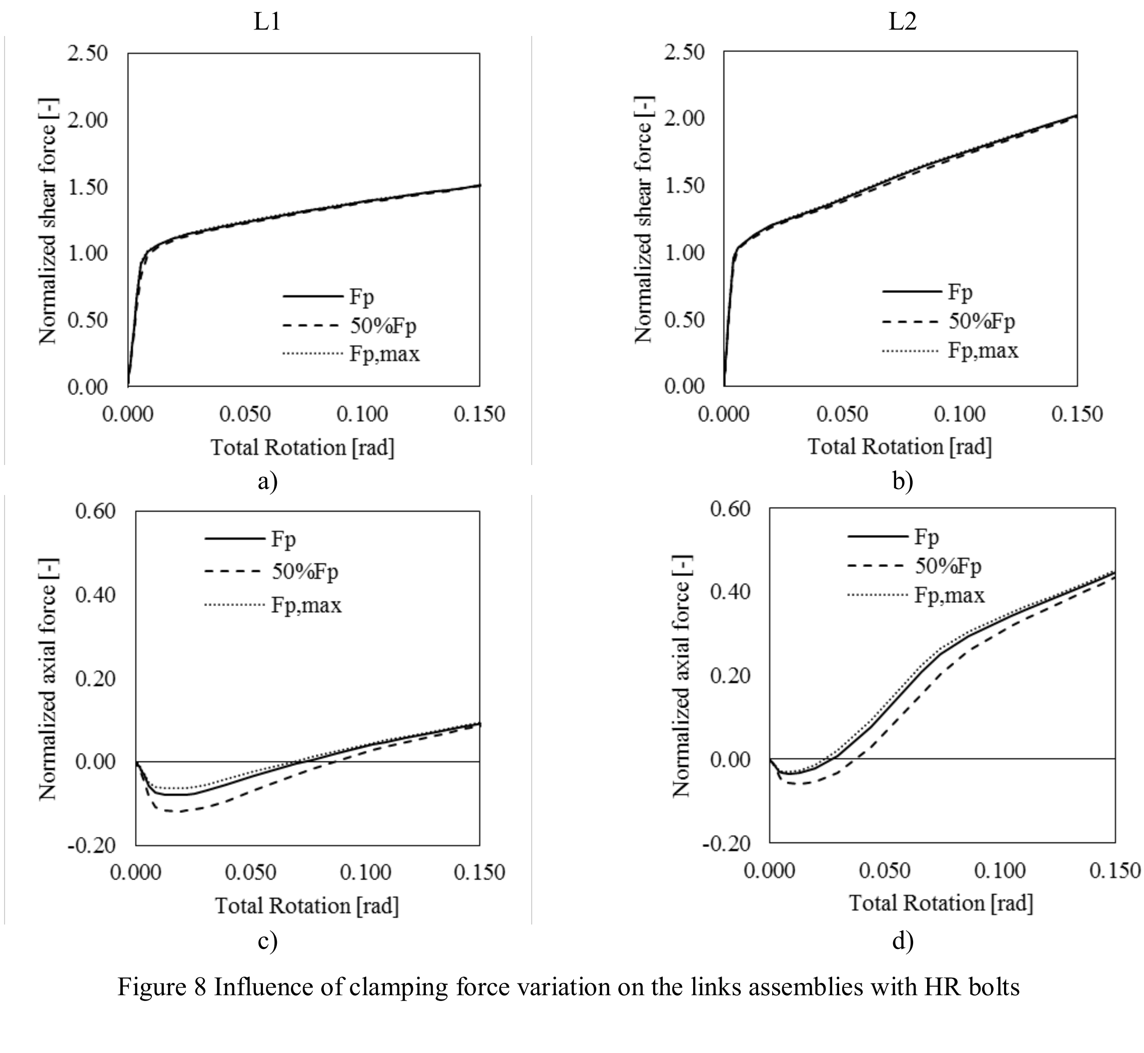


Figure 8 Influence of clamping force variation on the links assemblies with HR bolts

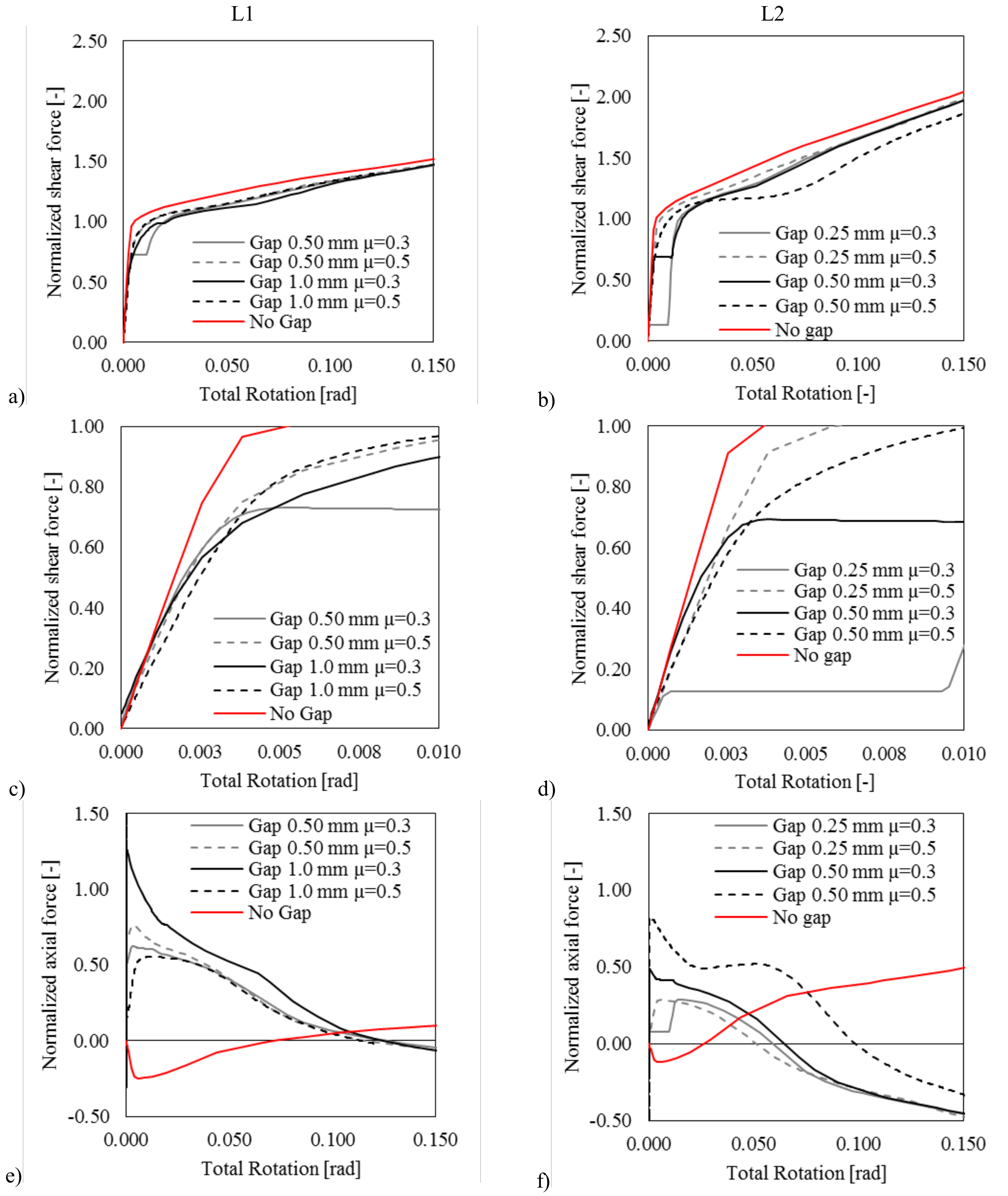


Figure 9 Influence of the constructional tolerance and surface preparation on the Shear and axial force developed in the links considering HR bolts and fully restrained boundary conditions

4 CONCLUSIONS

Based on the results of the parametric study carried out, the following conclusions can be drawn:

- The types of pre-loadable high strength bolts (i.e. HR and HV) have limited influence on the response of detachable links provided that the bolts are poorly engaged in the plastic response of the link- connection assembly.

- The response of the link in terms of stiffness and yield shear force is scarcely affected by the boundary conditions. However, the shear overstrength and the axial force developed in the link are highly dependent on the restraining conditions. Indeed, increasing the stiffness of the end restraints and reducing the link length lead to larger catenary actions developing in the links.
- The level of bolt pretension does not to affect the shear overstrength, but it leads to variations in the axial force. However, the difference tends to disappear for high levels of rotation when the clamping is no longer effective.
- The constructional tolerances and surface preparations for the connection end-plates can affect the response of the link-to-connection assembly, particularly by reducing the shear overstrength and increasing the axial force.

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