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SEISMIC NON-LINEAR TIME HISTORY FINITE ELEMENT ANALYSIS OF GLOVEBOX TUNNEL SYSTEM

Stephen HORROCKS[1], Andrew BUCKLEY[2], David SHAW[3] & Paul DOYLE[4]

Abstract: *A glovebox tunnel system utilises a chemical bond between the glovebox flexi-feet and the supporting concrete slab, the strength of which has been ascertained via in-situ test work. The failure of the bond(s) during a seismic event has the potential to compromise the containment boundary. As part of a Periodic Review of Safety a requirement was placed on the bond performance under a seismic event with an annual probability of exceedance of 1 in 10,000 years and hence demonstrate that the containment boundary is not compromised. The methodology was to generate an ABAQUS Finite Element model of the coupled concrete building (including soil springs) and glovebox/tunnel system. The potential for bond failure was included by using connector elements that had the prescribed bond strength. Other non-linear stiffness effects were included such as gaps and bolted gasket connections. Non-linear material properties for the stainless and carbon steel were also defined. A number of modified real seismic time histories were used to drive the model at the soil springs located at the base of the building. Assessment of the containment boundary was performed at every time step throughout each seismic event. This included monitoring the number of bond failures and the steelwork plastic strain, and calculation of the bolted gasket connection utilisations. The analyses demonstrated that the containment boundary was not compromised, even though a significant number of bonds failed. Based on this result it was recommended that no costly retrofits were required.*

Introduction

A two storey windowless reinforced concrete (RC) building, with shear walls, support columns and ground floor, first floor and roof slabs contains, on the first floor, a series of gloveboxes and tunnels (steel box sections used to transfer items between the gloveboxes) that form an interconnected system for processing operations. The gloveboxes and interconnecting tunnels are typically stainless steel shells supported on mild steel angle frames that are in turn supported on flexi-feet (cantilevered steel rods centrally located within displacement limiting steel cylinders) that are bonded to the first floor slab. In addition, a small number of atypical boxes are supported on Anti-Vibration (AV) mounts rather than flexi-feet.

The various gloveboxes and tunnels are joined with bolted flanged joints, sealed with a rubber gasket. However, for items on anti-vibration mounts, flexible bellows are provided with shouldered bolts limiting the allowable movement across the joints.

The purpose of this seismic analysis and assessment was to demonstrate that during a seismic event the containment boundary is maintained, i.e. deformation and movement could be tolerated proving that a breach does not occur.

Seismic Hazard

The 10^{-4}/yr. seismic hazard for the site was defined by the site specific Uniform Hazard Spectrum (UHS). Due to the highly non-linear nature of the seismic response of the gloveboxes and tunnel system, Time History (TH) analysis was adopted. The adoption of TH analysis allowed for the

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[1] Engineering Manager, ABS Consulting Ltd., Warrington, UK, shorrocks@absconsulting.com
[2] Principal Engineer, ABS Consulting Ltd., Warrington, UK
[3] Principal Engineer, ABS Consulting Ltd., Warrington, UK
[4] Jacobs UK, seconded to AWE, UK as Seismic Technical Authority

various interfaces between the gloveboxes and tunnels themselves and with the building to be captured.

ASCE 4-16 and ASCE/SEI 43-05 have set criteria for non-linear TH analysis. Specifically, when undertaking non-linear TH analyses, ASCE 4-16 Cl 4.7.3(b) requires that '*A minimum of five independent sets of three-component acceleration time series shall be used for analysis*.' and ASCE 4-16 Cl 4.7.3(c) states that '*The seismic response shall be taken as the average response from the five response history analyses*.'

Therefore, five sets of time history components were generated and the average of the response taken from the results of these five.

For the sets of time history components, ASCE 4-16 points the analyst to the guidance for their generation presented in ASCE/SEI 43-05 Section 2.4. One key requirement is the use of '*Actual recorded earthquake ground motion or modified recorded ground motion shall be used for nonlinear seismic analyses*' as the seismic input data in the suite of analyses. This involves the production of input THs using real source earthquake information. As such, a set of real THs was generated to match the input ground motion spectra, using the following methodology.

The initial screening of suitable THs allowed the determination of suitable THs that possess acceptable spectral shapes when compared to the target spectrum. The search filtered THs by using magnitude and distances, determined in accordance with guidance in NUREG/CR-6728.

Following the initial identification, the THs were matched against their respective directional target spectra using RSPMatch09.

The THs selected for use were baseline corrected. To verify that the baseline correction hadn't significantly changed the characteristics of the THs, the ground motion parameters were checked against those prior to baseline correction to verify that any changes were acceptable.

The matched response spectra were checked against ASCE/SEI 43-05 to ensure compliance and acceptability of the matched THs. This included the necessary correlation checks between the THs once they were grouped into suites to represent the two horizontal and vertical directions.

Fifteen THs were split into five sets of three that comprise of a TH for each principle direction (two horizontal and one vertical). These TH suites were then used as input into the FE model. An example of a suite of THs is shown in Figure 1.

More detailed information regarding the time history generation can be found in SECED Conference Proceedings 2019 "Practicalities, Decisions and Compromises in the Development of Modified Real Time Histories".

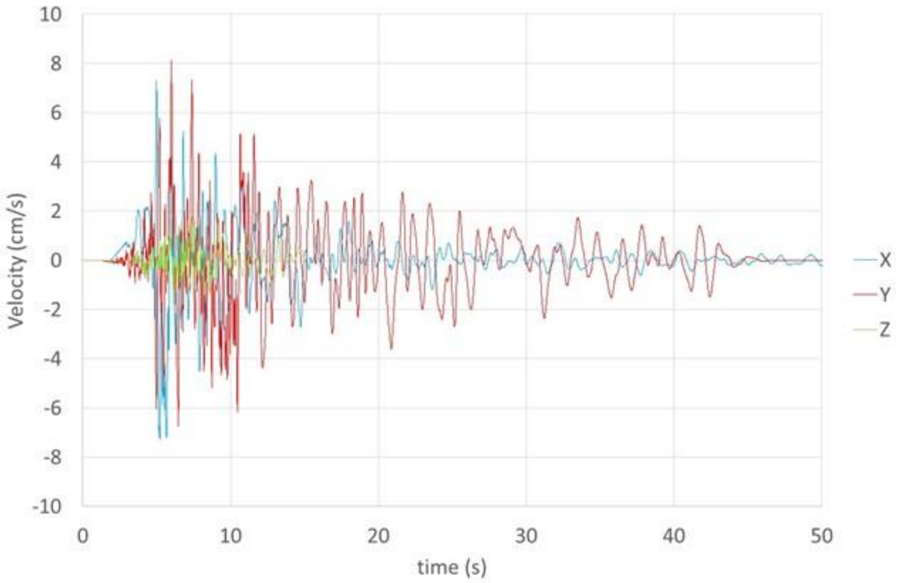


Figure 1. Modified Real Velocity Time History.

Finite Element Model

Overall Description

A non-linear TH analysis of the coupled building/gloveboxes/tunnels using ABAQUS needed to be performed in order to assess the adequacy of all bond and all other interfaces that maintain the containment boundary.

An FE model of the concrete building supported on soil springs was generated. The walls, floors and roofs of the building were modelled using linear first order shell elements (ABAQUS type=S4R). These elements gave an accurate representation of in-plane shear and out-of-plane bending, which both contribute to the dynamic response of the roof, walls and floor during an earthquake.

The roof down stand beams were of a deep section and were modelled using shell elements to accurately represent the fixity at their interface with the exterior walls of the building and roof void corridor beams. The corridor beams were similarly modelled to accurately represent their connections to the external walls and building columns. The building columns were modelled using linear beam elements (ABAQUS type=B31), which give good shear and bending characteristics. The mass of secondary steelwork and services within the roof and corridor voids was represented by point mass elements (ABAQUS type=MASS) spread along the nodes of the main roof down stand beams.

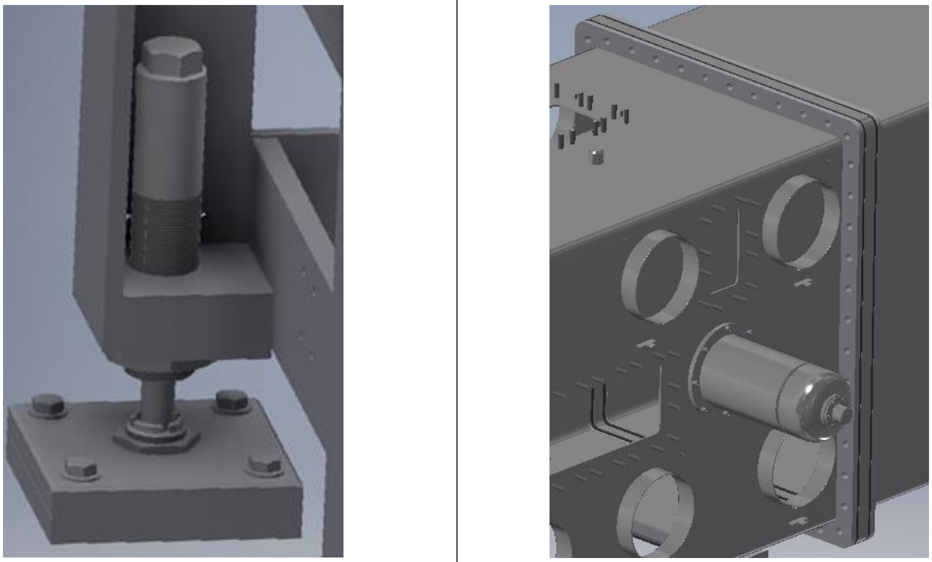
The longitudinal tunnel and supports were modelled using beam elements and included representations of the various supports whereas the gloveboxes were modelled using shell elements. A FE representation of the gloveboxes and tunnels was then incorporated into the building FE model as shown in Figure 2. Material non-linearity was also prescribed for the carbon and stainless steelwork. The number of boxes and tunnel segments totalled approximately four hundred and hence resulted in a significantly large FE model (130,000+ elements).

Figure 2. Portion of the Finite Element Model Showing Main Features.

Connection Types

The various boxes and tunnels that represented the containment boundary were connected together via various ABAQUS elements/constraints such as Connector Elements (CONN3D2), Multi-Point Constraints (MPC), Gap Elements (GAP), Tied Contact Surfaces (TIE), etc. The connections are shown in detail in Figure 3 and example locations are indicated in Figure 2. They include the following assemblies:

- Flexi-foot (supporting the majority of the typical gloveboxes and lateral tunnels),
- Bolted gasket (connects together the majority of typical gloveboxes and tunnels),
- AV mount (fixed to the floor beneath, or fixed to the base of atypical gloveboxes),
- Bellows (connects together atypical gloveboxes).


FLEXI-FOOT
BOLTED GASKET

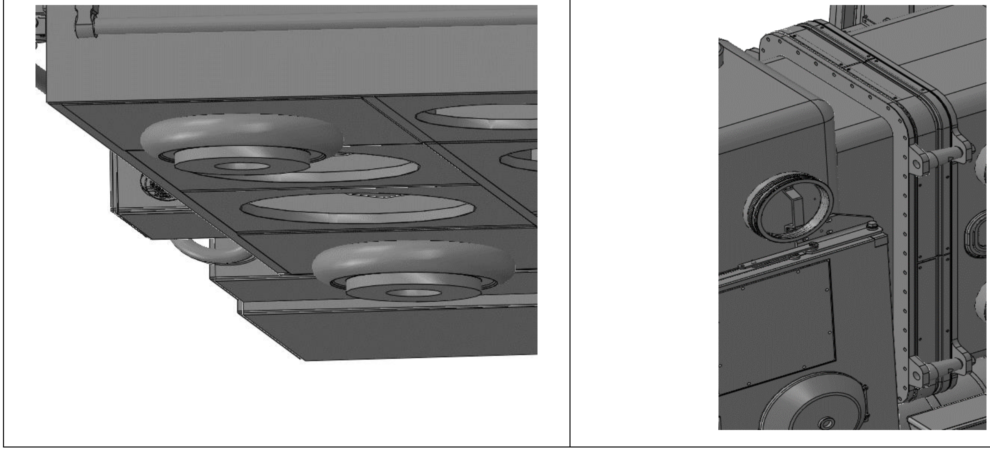

AV MOUNT
BELLOWS

Figure 3. Connection Assemblies to be represented in the FE Model.

The flexi-foot assemblies are used extensively throughout the facility and support hundreds of gloveboxes and lateral tunnels. The flexi-foot modelling and a section through an actual flexi-foot are shown schematically in Figure 4.

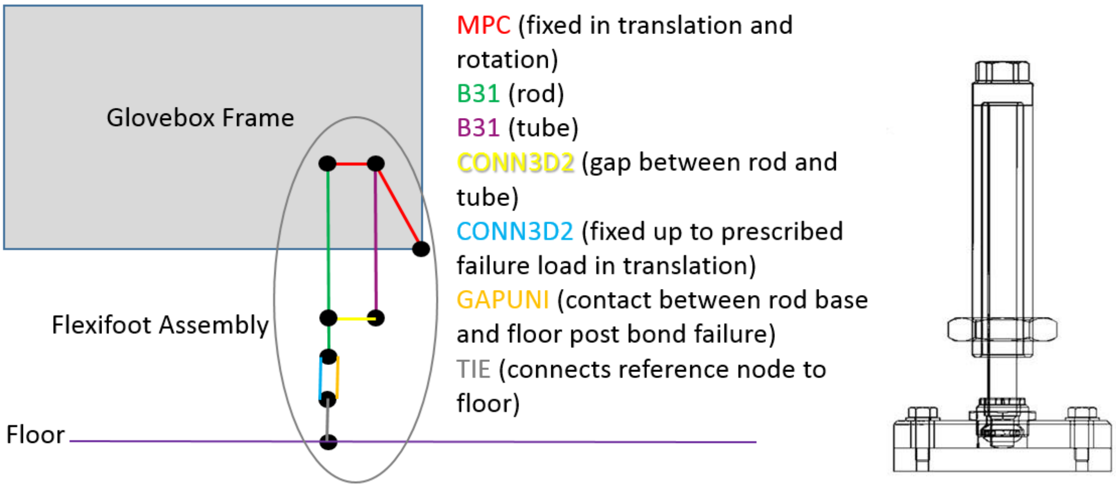


Figure 4. Finite Element Representation of Flexi-foot.

The flexi-foot tube (ABAQUS type=B31) was rigidly connected to the frame (ABAQUS type=*MPC). The flexi-foot rod (ABAQUS type=B31) was located inside the tube and was rigidly connected (bolted) to the top of the tube via an MPC. The rod to tube connection was modelled with a connector element (4mm gap in the radial direction, ABAQUS type=CONN3D2). The base of each rod was pinned (gimbal joint) to a reference node with a connector element which also had failure values defined corresponding to the bond strength which was ascertained via in-situ test work. In parallel with the connector element, a gap element (ABAQUS type=GAPUNI) was defined which also had a coefficient of friction prescribed. The reference node was rigidly connected to the supporting concrete slab (ABAQUS type=TIE).

The behaviour of the simplified representation of the flexi-foot under lateral loading was verified using detailed sub-modelling and, the assumption that the gimbal joint acts as a pin. The resulting lateral force-displacement characteristic of the flexifoot assembly is shown schematically in Figure 5. The cantilevered rod bending up to closure of the gap and then the stiffer 3-point bending of the rod in the tube can be clearly seen.

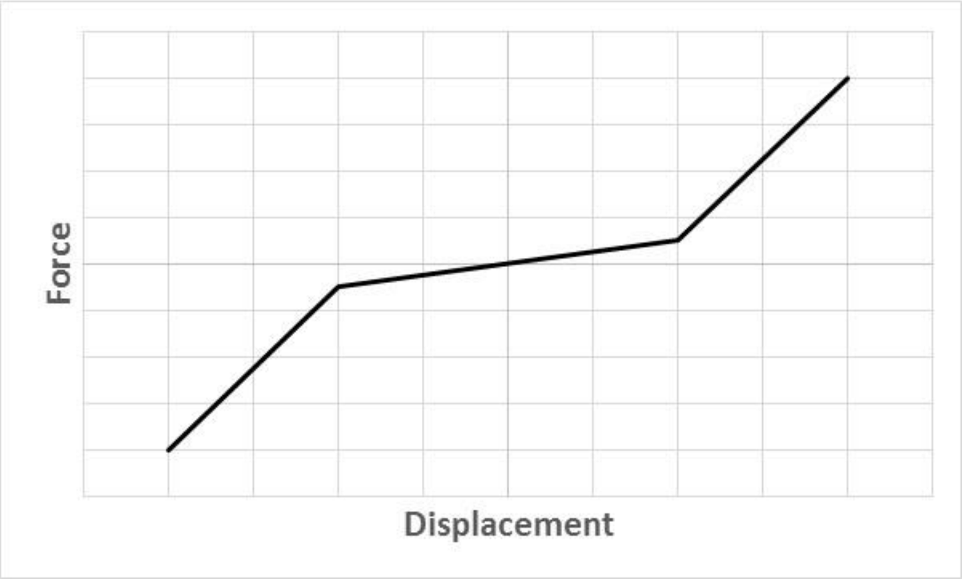


Figure 5. Lateral Force and Displacement Characteristic in Flexi-foot Assembly.

The flexi-foot is the most complex of the connection assemblies. The other connections are briefly discussed below.

The AV mounts beneath atypical boxes were modelled using a combination of connector and gap elements with appropriately tuned stiffnesses for the AV mounts, bond failure for those arrangements that possess a bond, and gap elements to represent potential uplift.

The Bolted Gasket Connections between typical boxes were modelled using connectors with bi-linear stiffness properties to represent the compressive and tensile behaviour as well as the moment stiffnesses. The stiffnesses were determined using detailed sub-modelling of the joints.

The Bellows between atypical boxes were modelled using connector elements with gap values prescribed to represent the amount of movement allowed by the connection.

In total, there were 5500+ connectors and 1500+ gap elements in the amalgamated FE model.

Performance of Connections

An example of one of the key connections in the model is discussed below. The flexi-foot has been chosen as an illustration because of the significant number of these assemblies in the FE model.

Figure 6 shows a time history of the lateral gap and contact force between the rod and tube during the seismic event. It can be seen that the lateral gap never exceeded the 4mm prescribed separation. Where the 4mm was reached and the gap closed, a contact force was developed, and the tube became laterally loaded.

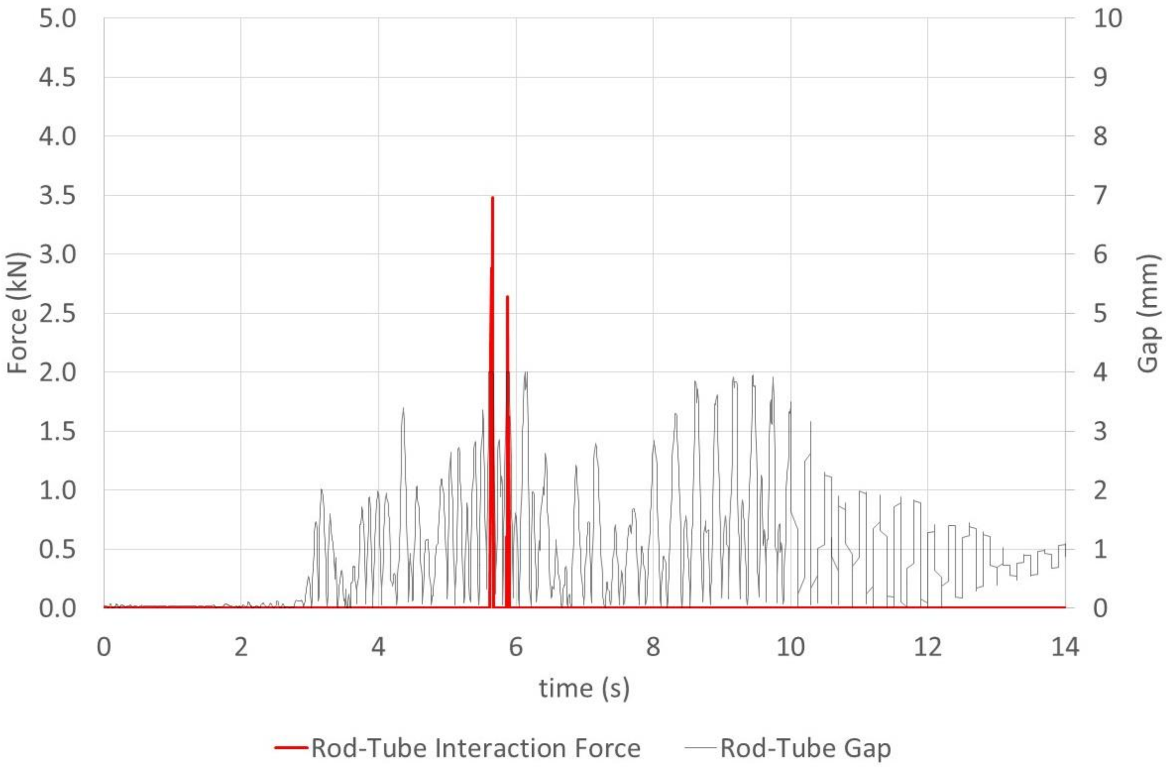


Figure 6. Lateral Force and Displacement in Flexi-foot Assembly.

Figure 7 shows a time history of the vertical gap and contact force at the bonded connection during the seismic event. It can be seen that there was a vertical compressive load in the connector at the beginning of the seismic event and this represented the self-weight of the supported glovebox. As the seismic event proceeded, the compressive load in the bond oscillated and eventually became tensile. When the tensile capacity of the bond was reached, the connector was automatically deleted from the analysis. At this point the flexi-foot had uplifted and eventually returned to ground. The gap element that was defined in parallel with the now deactivated connector element carried the compressive support load. Whenever the compressive load was relieved, the load in the gap reduced to zero and a vertical displacement can be seen. Any lateral displacement was somewhat constrained by friction when the gap element was carrying compressive load.

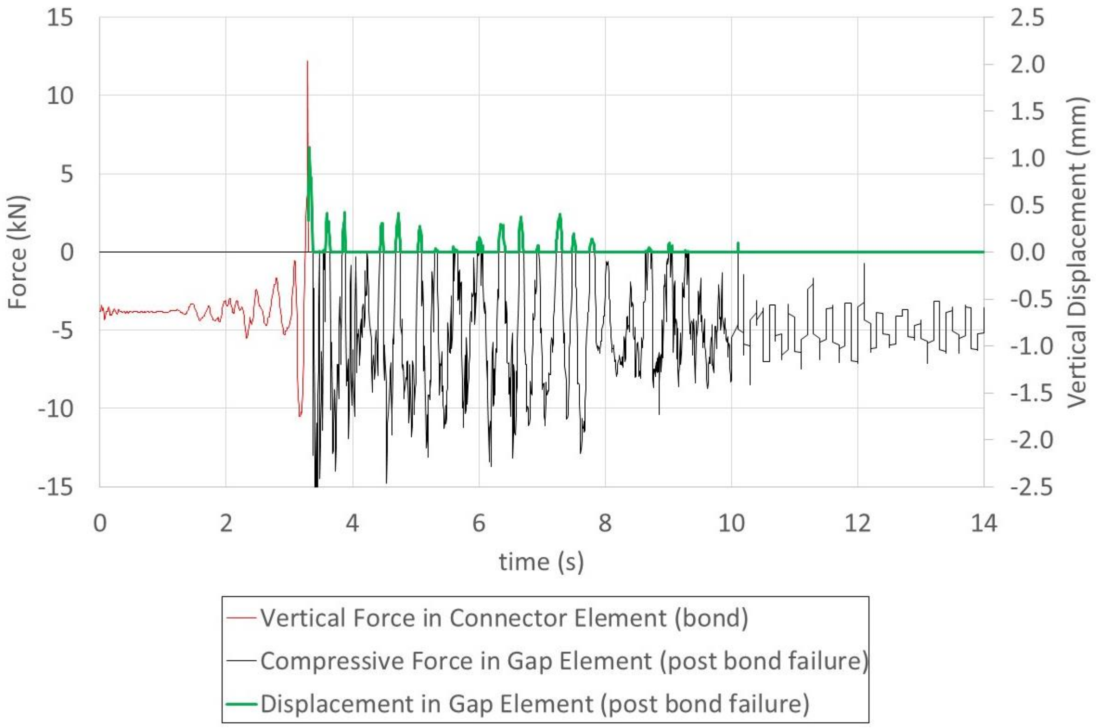


Figure 7. Vertical Force and Displacement in Flexi-foot Assembly.

Results

The best estimate model was analysed for five suites of time histories and the results averaged. All bonded connections were monitored, and a failure probability assigned to each one; see Figure 8. It can be seen that the predicted bond failures were extensive at the typical gloveboxes whereas there were less failures at the lateral tunnels and no failures at the AV mount supported atypical gloveboxes.

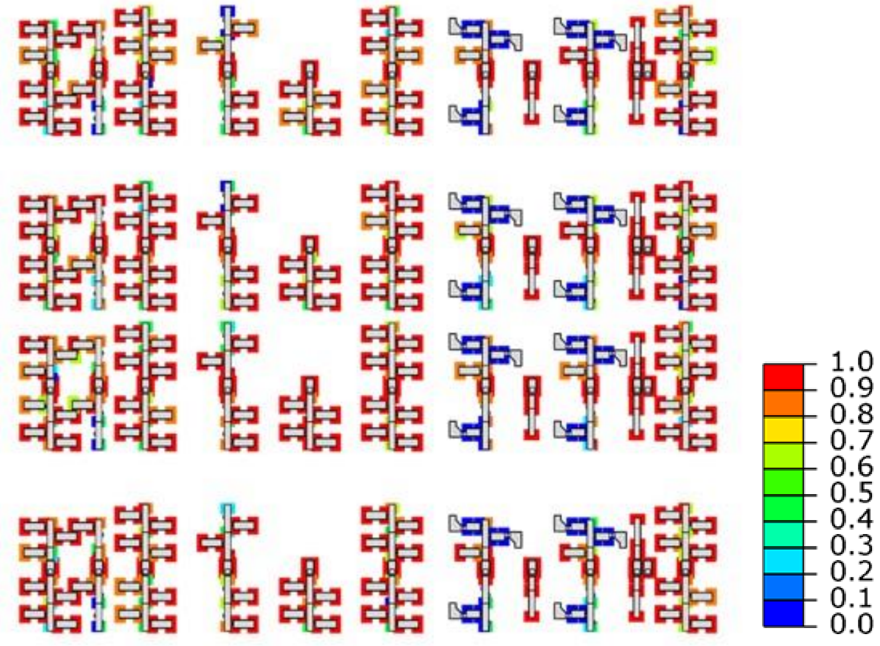


Figure 8. Probability of Bonded Connection Failure.

Even though bond failure did not in itself result in loss of the containment boundary, the bond failure could potentially lead to loss of containment through failure of other connections. The bolted gasket connections have also been assessed and the utilisations averaged over the five time histories. It can be seen from Figure 9 that even though there was predicted to be extensive bond failure, the bolts remained lightly loaded.

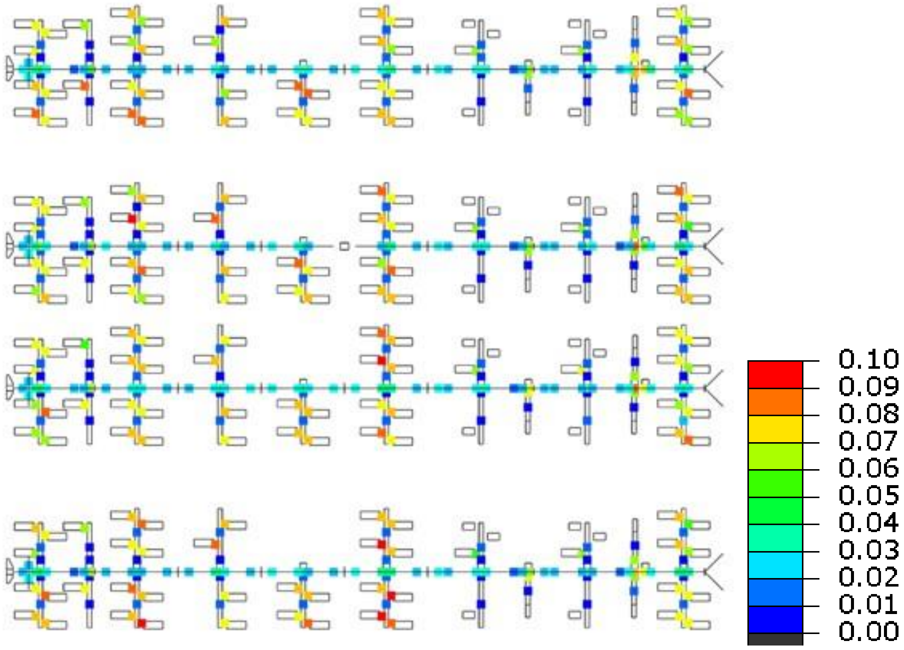


Figure 9. Gasket Bolt Average Utilisations.

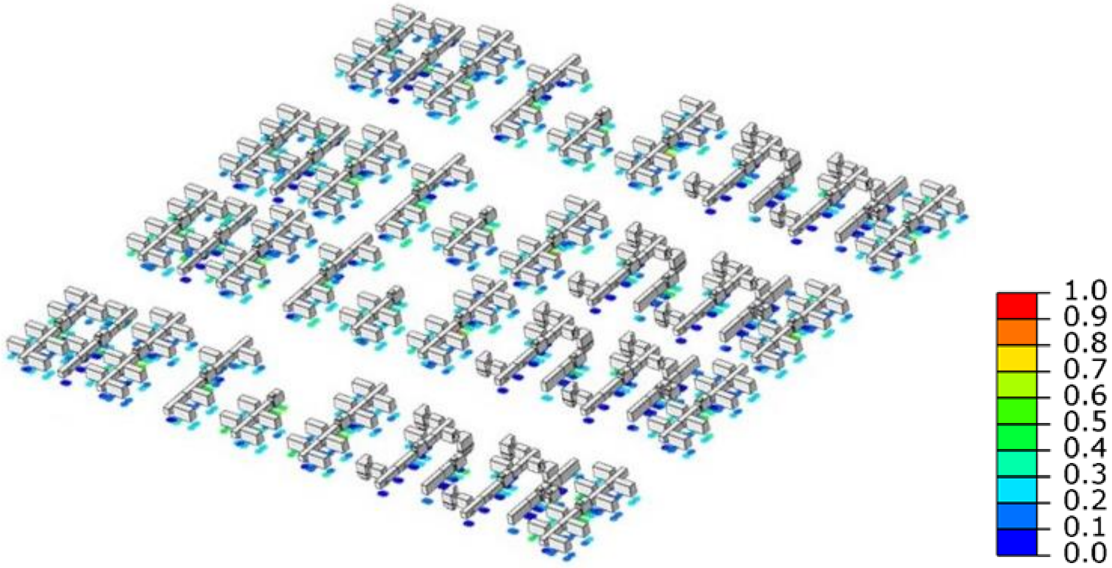


Figure 10. Flexi-foot Average Percentage Plastic Strains.

In addition to showing that all connections of the containment boundary retain their integrity, the glovebox and tunnel steelwork were checked to ensure no rupture was being predicted by the FE model. The only material plasticity was noted in the flexi-foot rods; see Figure 10. However, the level of plastic strain was small (<1%) and rupture of the material was dismissed as a concern.

The bond strength and the values of other key parameters such as friction and bolted gasket connection stiffness were chosen so as to represent a best estimate of the system response. Numerous sensitivity studies were also carried that investigated these parameters further. For example, the assumption of high bond strength and low bond strength looked to cover the uncertainty in the best estimate bond strength. A high bond strength results in a stiff system that maximises loads whilst a low bond strength results in a weak system that maximises displacements. For all of the sensitivity studies undertaken, the containment boundary was shown to retain its integrity.

Conclusions

FE analysis of a glovebox and tunnel system was performed in order to assess the integrity of the containment boundary around the tunnel interconnecting joints. The FE model contained thousands of non-linear connections, non-linear material properties and modified real time history seismic input motion.

Analyses were performed on the best estimate model for five time histories suites and the results averaged. The key results were as follows:

- Bond failure at flexi-foot connections of typical boxes was extensive although there were no failures for atypical boxes sat on flexible AV mounts.
- The bolts at the gasket connections were lightly utilised and the maximum gasket compression was found to be easily accommodated by the gaskets with no damage to their function.
- The bellows bolts between atypical gloveboxes were highly utilised but remained within the code allowable.
- Maximum displacements remained small enough so as not to compromise attached services.
- The peak plastic strain was ~1% which is well within the steel rupture strain.
- Glovebox and tunnel shells and frames remained elastic.

Based on the results of the averaged best estimate model, it was concluded that the containment boundary retains its integrity during the postulated 10^{-4}/yr. seismic event and no retrofits were required for mitigation. Based on the results of the individual and combination sensitivity studies, it was found that the conclusions drawn from the best estimate model remain valid.

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