# Chapter 19
# Monitoring the Interface Behaviour of Bolted Joints

**T. Mace, S. Gilbert, T. Moghadam, and P. Pandey**

**Abstract** Validating the localized nonlinear contact behaviour of a jointed structure is a challenging task. This is because monitoring the interface during a vibration cycle, to identify stick, slip and separation zones, without changing the interface, is very difficult. Total Internal Reflection has recently been used at Imperial College London to measure the interface conditions of simple, well controlled joints, where two transparent interfaces were illuminated via a laser and the reflected/transmitted light from the interface was recorded. The change in reflection/transmission can reveal localised contact zones and show their transition from stick to slip during a vibration cycle. This work applies the Total Internal Reflection (TIR) technique to more realistic lap-jointed structures. The structures investigated were based on the well-investigated Brake-Reu$\beta$ beam but manufactured from transparent PMMA to facilitate the novel testing approach. Bolt loads and excitation were well controlled via the use of instrumented bolts, and rigorous modal testing, and TIR measured using a high-speed camera and expanded laser beam. For the first time, this has allowed for the production of a fuller picture of the contact conditions during the vibration cycle of a realistic jointed structure.

**Keywords** Optical · Contact · Joint · Vibration · Interface

## Introduction

In most large engineering structures, such as turbomachinery and load bearing structures, elements of the structure will be fastened together via bolted joints. Here, an interface, consisting of two contact surfaces and one or more bolts exists, which drastically alters the vibrational characteristics of the system. Vibration results in High Cycle Fatigue (HCF), due to high vibration amplitudes and intense cyclic stresses. The friction in such joints provides a certain amount of damping to the structure, reducing vibration amplitudes, but the behaviour of the joints is unpredictable because the vibration response is often highly nonlinear, with the damping and resonances varying significantly with vibration amplitude [1]. There nevertheless exists the fact that it is very difficult to physically measure the contact conditions inside the contact interface during a vibration cycle without physically altering the interface, limiting the physical understanding that underpins the simulations, which must instead utilise smeared contact stiffness parameters obtained experimentally for an entire interface contact, without the consideration of local behaviour. There have been extensive attempts to improve upon the understanding of the contact interface behaviour using experimental techniques. These studies have typically involved high-speed cameras and Digital Image Correlation (DIC), which allows for the observation of the contact along the edges of an interface to impressive levels of detail, but still not within the interface [2]. Other novel measurement techniques have involved the use of two aligned LDVs on either side of a flange-like interface, but have been limited in spatial resolution[3]. Furthermore, alternative approaches

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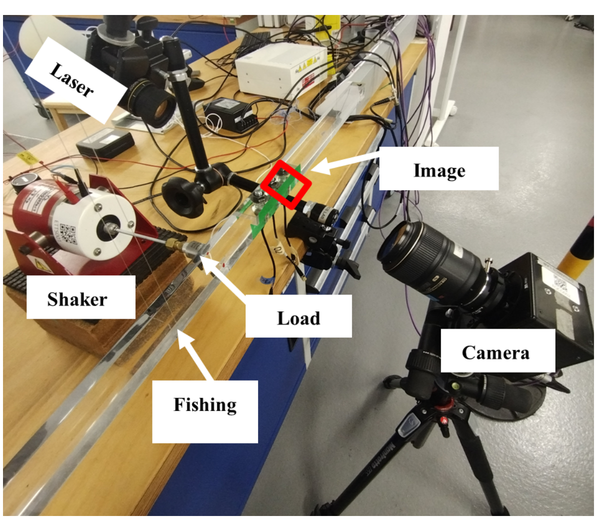
using Acoustic Emission (AE) [4]are somewhat limited in measuring the stick-slip transition of an interface due to the loss of the AE signal to the noise floor of the experiment for certain test specimens and configurations. By comparison, a promising technique utilises Total Internal Reflection (TIR), whereby transparent specimens are used, and the contact interface is illuminated with an expanded laser beam. High-speed camera measurements can subsequently capture the change in luminance across the interface, with different greyscale values attributed to areas that are in full contact, slip and separation. This technique has been successfully used, in combination with hysteresis loop measurements, to assess the affect of frictional forces upon the real area of contact of a small, sliding interface [5]. The study details the application of this novel approach upon a larger, bolted interface.

## Materials and Methods

The structure chosen for the application of TIR is the well-documented Brake-Reu$\beta$ Beam (BRB), consisting of a lap joint with three bolts tightened to equal torque levels [6]. Unlike all BRBs thus far, the two structures examined were manufactured from cast PMMA, which was milled to produce the lap jointed region, but is otherwise of the same dimensions as a standard BRB. A monolithic beam, of the same dimensions but with no lap joint, was used to benchmark the effects of the test setup. Instrumented bolts with load calibrated strain gauges [7], were used to provide an accurate and consistent bolt tension of 3000N across the three bolts, improving upon the usual error margins of a torque wrench. A back-of-the-envelope calculation estimated a plastic limit torque of approximately 10Nm for the M8 bolts and PMMA. A laser source (Coherent – VLM 0.6mW 635nm) was connected to a laser beam expander (Edmund Optics 20x VIS-NIR Vega BB) with a 3D printed adaptor to increase the area of illumination and mounted at approximately 60$^o$ to the contact interface. A Photron Mini-UX100 high-speed camera, running at 4000FPS was placed colinearly with the laser, to capture the illuminated contact area. The vibratory motion of the beam, due to shaker excitation, was removed using the Photron PFV software's in-built stabilization algorithm. The technique takes advantage of the principle that the transmitted light intensity across each pixel is a proportional to the real area of contact, since at areas which are not in contact, light will be reflected, and at areas in contact, light will be transmitted directly through the interface. In reality, the resolution of each pixel is larger than that of a micro-contact region, so the effective contact area is assessed through the light intensity, rather than binary, 'light or dark' values. A DataPhysics Quattro and Shaker, with a PCB Accelerometer (352A21) and Dytran load cell (1051V2) were used to measure and control the vibration of the structure at three excitation levels (1N, 5N and 10N), and a manual trigger connected to the force channel of the DAQ and high-speed camera allowed for tacho-syncing of the two data streams allowing the position of each captured image within the vibration cycle to be tracked. The test specimens (monolithic, cast-jointed and 3D-printed) were suspended by a light, inextensible fishing wire through the nodal locations of the first bending mode, to minimise damping from the boundary conditions. The shaker and accelerometer were attached at the location marked in Figure 1b and the camera-laser setup directed to the region at the end of the lap joint, where motion is most expected to occur, since the expanded laser beam was not large enough to illuminate the entire length of the contact interface. Both in-plane (IP) configurations, with the

(a)




(b)

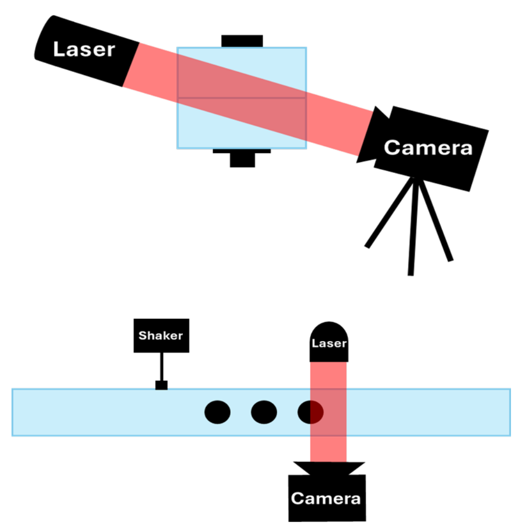



**Fig. 1** Physical Test Setup (a) and Schematic (b) Detailing the Approximate Region of Interest.

bending motion in the plane of the contact interface, and out-of-plane (OP) configurations, with the beam rotated through $90^o$ along its length, were examined for each test case. The first three bending modes were examined for each test configuration.

## Results

Initially, roving impact tests on the monolithic beam and all BRB specimens allowed for the determination of the natural frequencies of each mode. Inherent material damping of the first mode found to be approximately 3% for the monolithic beam. Stepped-sine measurements of the monolithic beam at three different forcing levels (Figure 2) showed little significant shift in the natural frequency or damping of the first two modes. As such there is only marginal nonlinearity due to the viscoelastic material or shaker test set-up at forcing levels of up to 10N. Conversely, the BRB specimens showed more significant nonlinear behaviour at higher forcing amplitudes, which can likely be attributed to the frictional bolted joint behaviour, with a 2%, 0.5% and 1% shift in frequency of the first three out-of-plane bending modes respectively. This alludes to potential micro-slip in the contact interface and allows for further investigation with the novel optical technique.

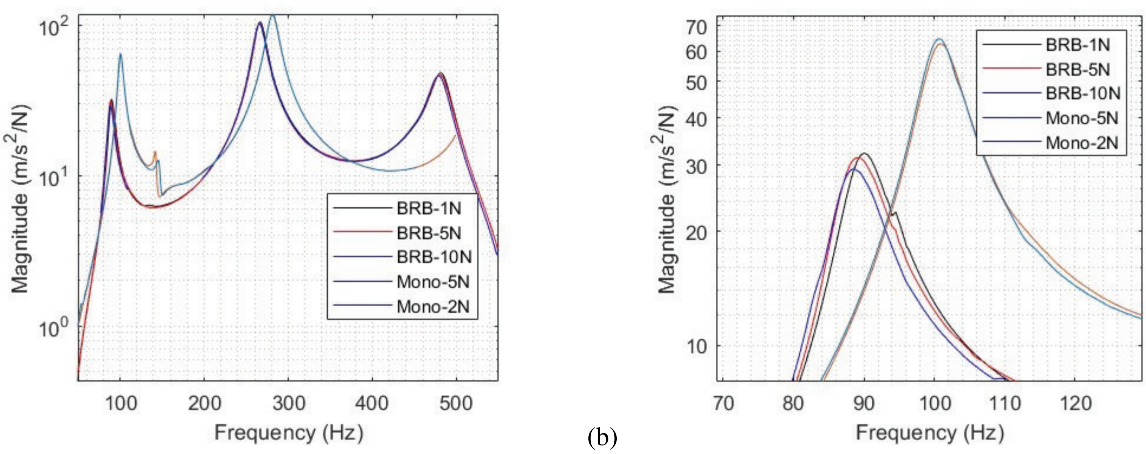
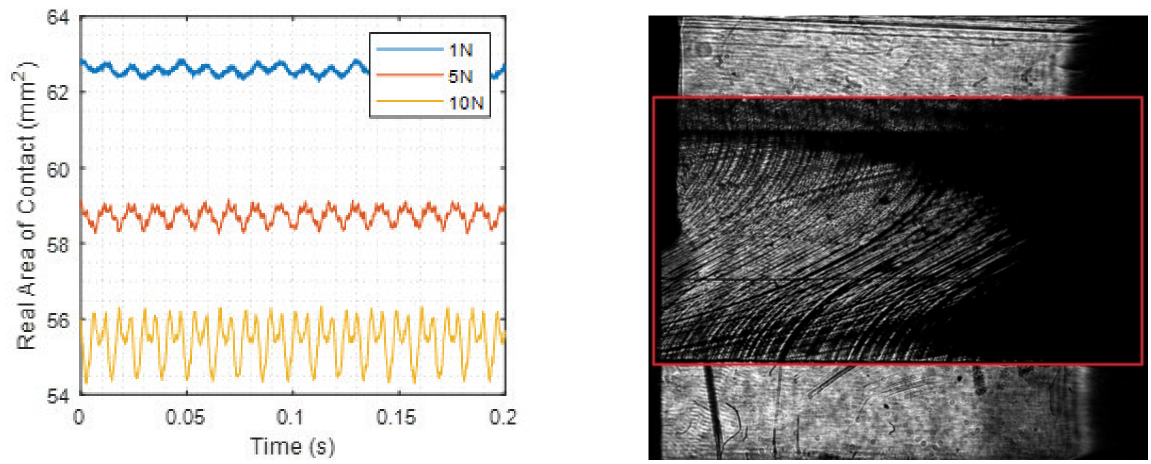



**Fig. 2** Comparison of Nonlinearity for the Monolithic/PMMA BRB for the 1st 3 modes (a) and a Close-Up of the 1st Mode (b).

Clear images and high-speed videos were captured of the 'end' region of the BRB contact interface. As a result of the footage stabilization, the laser beam moves relative to the laser and the laser has a inconsistent intensity distribution with multiple visible ring patterns. This can be observed across the vibration cycle in the captured images, reducing the ease with which the contact behaviour can be assessed.

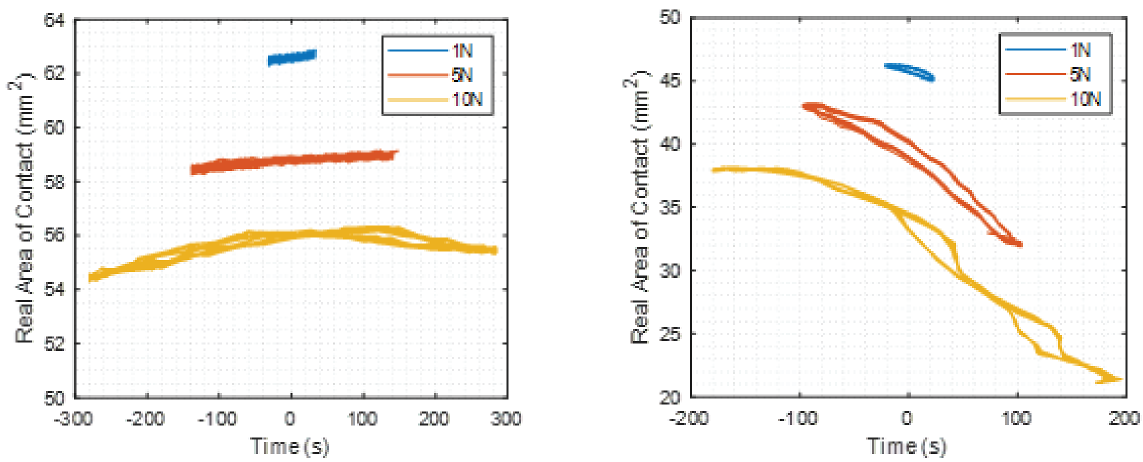
From Figure 3 the change in real area of contact can be observed, and this increases with a higher excitation load as might be expected. Additionally, it can be observed that the average contact area reduces as the excitation load increases. Whilst this suggests that the higher amplitude may results in greater slip, and therefore a reduced apparent contact, this may be an artifact of relative motion between the specimen and the illumination field, so requires further investigation.

Figure 4 demonstrates the ability of the test technique to capture the change in the real contact area across the vibration cycle. Both the IP and OP cases show an increase in the change in contact area across a vibration cycle, but in a different manner. The IP case clearly shows the maximum contact to exist in the middle of the cycle at the point of minimum displacement/acceleration, whereas the OP configuration shows the contact area to increase and decrease at either end of the cycle, showing the opening and closing of the interface as the specimen is vibrated out-of-plane with the contact interface. The overall change in contact area is greater for the OP configuration than the IP configuration (seen in Fig. 5a), presumably due to this mode of motion, in comparison to the shearing motion of the IP cases. Furthermore, Figure 5b highlights the regions of the interface that show the greatest change in contact area, showcasing the opening/closing region for the OP 10N $1^{st}$ bending mode, and providing insight into the physical change of the interface for this mode, information that could be used to inform more representative modelling.



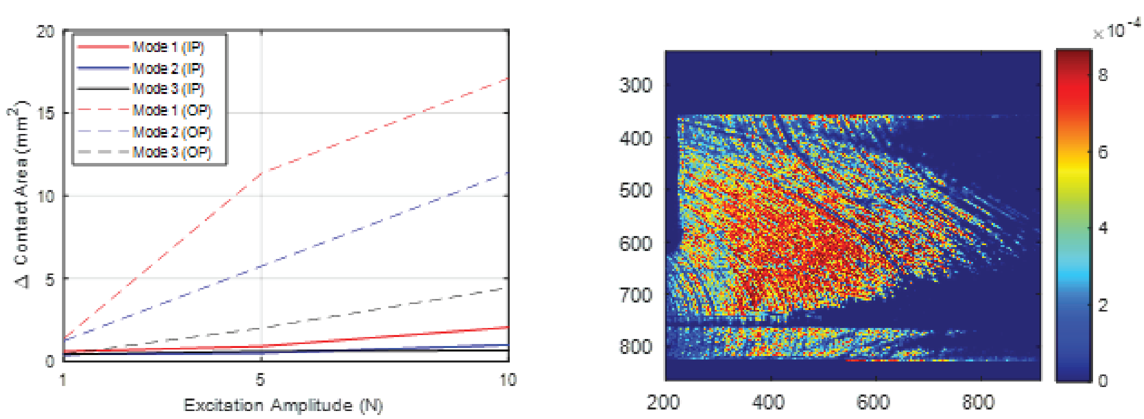

a) b)

**Fig. 3** Capture of the change in contact area for several harmonic excitation loads (a), and image of the illuminated contact interface (highlighted in red) (b).




a) b)

**Fig. 4** Change in Real Contact Area with Respect to Acceleration for a) the IP case and b) the OP case.




a) b)

**Fig. 5** a) Relationship between Excitation Amplitude and Change in Contact Area across 3 modes, both IP and OP b), the Distribution of Contact Area (mm2) Change for the 1st Bending Mode of the OP Configuration, at 10N Exc. Amplitude.

## Conclusion

The TIR measurement technique has demonstrated great potential for the further analysis of bolted joints, allowing for the study of the changes of contact area in the contact interface. Whilst further test refinement and analyses are required to explore the full capabilities and limitations of the test technique, the technique has allowed for the observation of expected relationships, providing confidence in the data produced, as well as producing a novel insight into the change in contact area across a vibration cycle which has been thus far unobserved in literature without the use of supplementary material in the interface. As such, this study has highlighted the potential for the further development and refinement.

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