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In Situ Measurements of Contact Pressure for Jointed Interfaces During Dynamic Loading Experiments

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Abstract One of the greatest challenges for developing and validating models for the dynamics of jointed interfaces is measuring and characterizing the contact pressure within a joint. Previous approaches have focused on static measurements, typically taken separately from the dynamic testing of a jointed system. In this research, an electrical contact pressure measurement system is used to measure the contact pressures within a jointed interface during dynamic testing of the jointed system. These experiments invalidate a previously held modeling assumption: that the static pressure distribution is representative of the contact pressure during service of a jointed interface. In fact, for the measurements reported, the extent and magnitude of contact pressures dramatically change across the interface during sinusoidal excitation of the

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jointed system with more than a quarter of the interface oscillating between being in and out of contact during each period of excitation. While preliminary and scoping in nature, these experiments corroborate recent numerical studies that predict that the contact pressures across an interface significantly change over time as a function of the applied loading. The ramifications of these results are that the energy dissipation mechanisms within a jointed interface significantly evolve over time, resulting in more energy being dissipated in the interface away from the bolts than previously anticipated. This, in turn, necessitates a new constitutive modeling approach for reduced order modeling representations of joints in which the local kinematics are not regularized (such as in traditional Iwan models) and the normal contact forces are directly modeled and allowed to vary with load (contrary to most of the current modeling approaches).

Keywords Joint Mechanics · Bolted Joints · Interfacial Mechanics · Frictional Dissipation · Wave Propagation · Dynamic Contact

1 Introduction

The modeling and prediction of the response of jointed structures is a challenging engineering problem for multiple reasons. First, the frictional interactions within the interface of a jointed structure are not well understood: Coulomb friction breaks down when used to describe the frictional energy dissipation and is unable to capture both macroslip and microslip effects within the same model (Segalman et al. 2009; Brake 2017). Further, the frictional characteristics of a jointed structure change over time as wear is accumulated (Ostermeyer and Müller 2006; Müller and Ostermeyer 2007b; Müller and Ostermeyer 2007a; Bode and Ostermeyer 2014; Mulvihill et al. 2011; Schwingshackl, Petrov, and Ewins 2012).

Second, the extent and evolution of the contact patch during dynamic excitation is unknown. Recent numerical studies have highlighted that the contact patch dynamically evolves over a period of excitation (Flicek et al. 2016). Complicating matters, though, is that the contact patch is unable to be directly measured during use as it is internal to a system. Methods to infer what may be occurring internal to the joint, by their very nature, change what the response will be (not unlike the observer effect in quantum physics (Heisenberg 1959)). Nonetheless, any information regarding how the contact patch evolves during dynamic excitation would be able to provide crucial insights to modeling. Allowing the contact patch to evolve in a dynamic model yields a much higher degree of agreement with experimental measurements (Lacayo et al. 2017).

This research seeks to develop new insights into the evolution of the contact patch by measuring the contact pressure within the interface in real time during dynamic excitation. While the measurement method (a polymer contact film inserted between the two mating surfaces) changes the response of the system, it is expected that meaningful insights can be developed from these results in order to improve the dynamic modeling and prediction of jointed structures. In what follows, §2 details the experimental setup, and the measurements are detailed in §3. Lastly, the ramifications of these results are discussed in §4.

2 Experimental Setup

To study the evolution of the contact pressure in the interface of a jointed system, the benchmark system of the Brake-Reuß beam is used (Brake 2017; Smith et al. 2015; Brake et al. 2014; Catalfamo et al. 2016). The Brake-Reuß beam (Fig. 1) consists of two stainless steel beams joined via a three bolt lap joint. While the system is straightforward to manufacture, the nonlinearity introduced by the lap joint yields a highly nonlinear response.

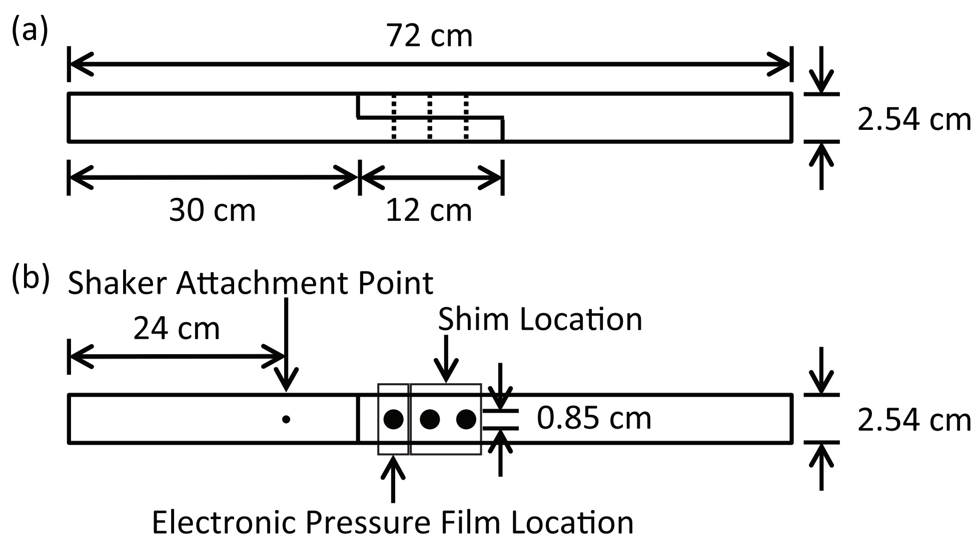

Fig. 1 The geometry of the Brake-Reuß beam for (a) top view and (b) side view. Note that the shaker acts in the direction orthogonal to the interface surface in view (a).

The system is setup similar to Fig. 2. The Brake-Reuß beam is suspended via two bungee cords connected to fishing lines to approximate free-free boundary conditions. An electromagnetic shaker is attached via stinger to the beam on one side of the interface. A force transducer and accelerometer at the stinger attachment location are used to control the shaker. In the following experiments, the shaker is operated in an amplitude control mode.

Pressure films developed by Sensor Products Inc that are 1 inch by 1 inch with 256 sensors (on a 16 by 16 grid) are used to measure the contact pressure in the interface in real time during the dynamic excitation of the system. In the following experiments, data is acquired at a rate of 488 Hz. In order to accommodate the pressure films, the interface configuration is modified from Fig. 2. The limitations of the pressure film used restrict the experiments to only 500 Psi in the interface. Thus, in order to not permanently damage the pressure film, the bolts are only tightened to 2 Nm. Additionally, only two bolts are used, with the pressure film centered about the third bolt hole (i.e. the bolt closest to the shaker location). Further, to relieve stresses in the pressure film, shims made from a similar material are inserted into the interface around the other two bolt holes such that there is an equally thick layer of material across the entire interface. While this changes the nature of the contact mechanics within the interface, the results from the following experiments are expected to still yield meaningful insights into how the contact pressure within the interface evolves during dynamic excitation.

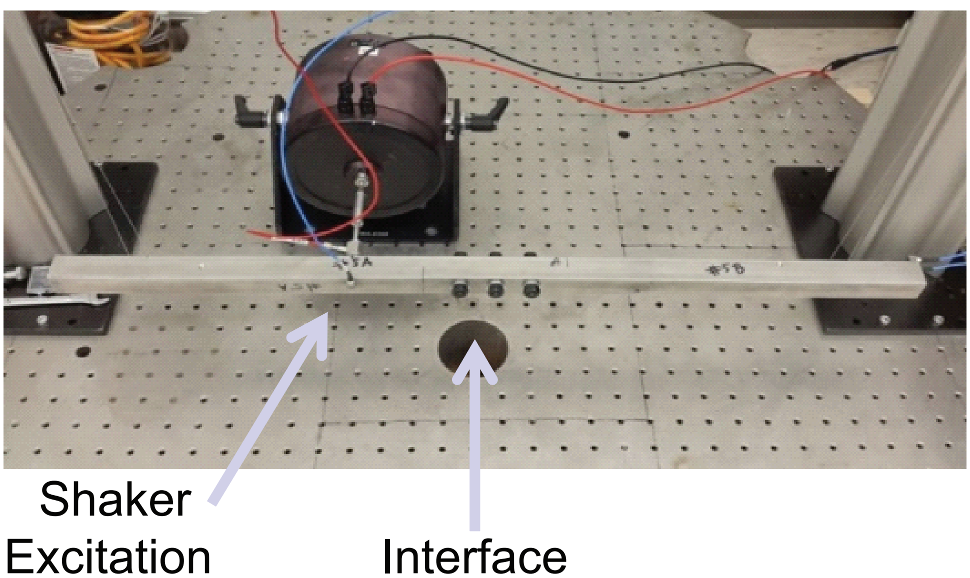

Fig. 2 The typical experimental setup for the Brake-Reuß beam.

For each experiment, the shaker is used to excite the Brake-Reuß beam over a narrow band of frequencies centered about the first natural frequency in order to study the transition through resonance. Real time measurements of the contact pressure in the interface were recorded, and are presented in Section 3.

In what follows, several caveats are important to keep in mind:

– The bolt torques are 2.0 Nm, compared to the nominal 20 Nm.
– Only two bolts are used to connect the interface.
– The interface contains a polymeric material, which changes the contact from metal on metal to metal on polymeric on metal.

3 Results and Discussion

As an initial inspection of the system, an experiment is conducted in which the excitation frequency is swept from 100 Hz to 160 Hz at a rate of 1 Hz/s with the shaker amplitude set to 4 N. The primary resonance of the system (including the pressure film) is located near 124 Hz. As the excitation sweeps through resonance (near 30 seconds), a significant change is observable in the contact area (Fig. 3). The contact area transitions from being a nearly constant value of 0.3 in^2 to varying between 0.05 in^2 and 0.35 in^2. After resonance has passed, the contact area returns to the nearly constant value of 0.3 in^2.

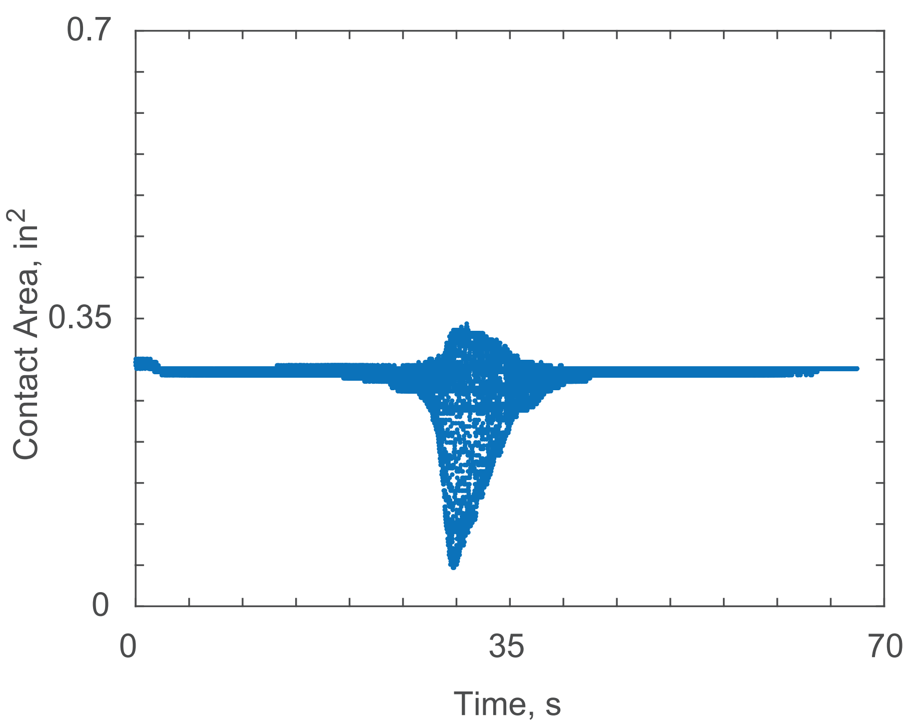

Fig. 3 Contact area as a function of time over the left quarter of the interface for the 100 Hz to 160 Hz sweep.

The contact force for the studied portion of the interface is calculated by summing the contact pressures over the interface and multiplying by the area of each pressure sensor $(1/16 \text{ in})^2$. The contact forces are observed to vary significantly about resonance. Below resonance, the contact force in the left quarter of the interface is observed to be constant at approximately 60 lbs. Near resonance, however, the contact force varies between 2 lbs and 70 lbs. At frequencies above resonance, the contact force returns to a constant value (though increasing slightly with frequency) of approximately 62 lbs.

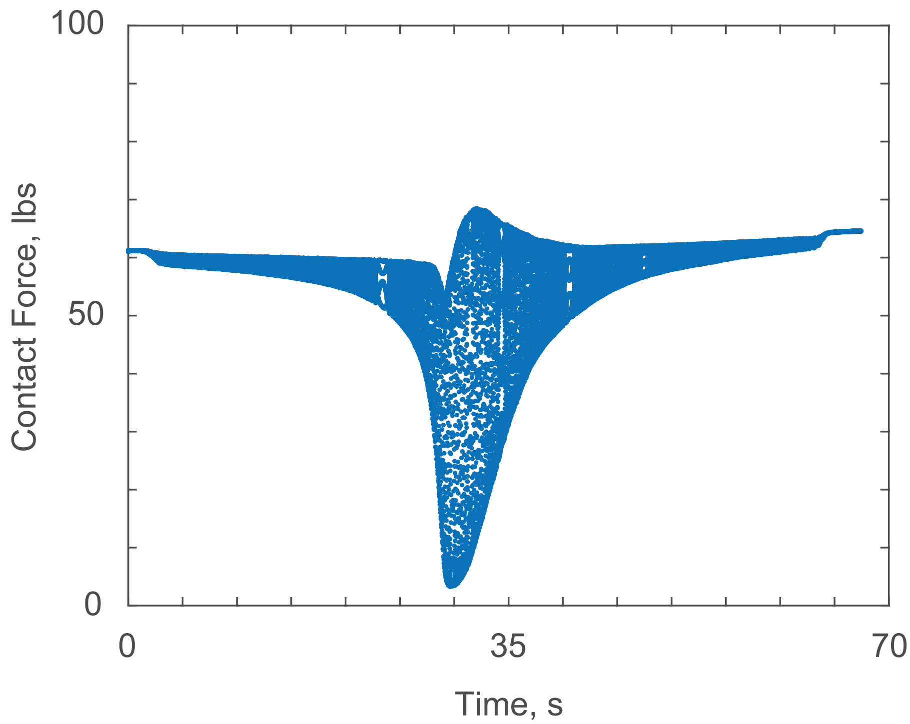

Fig. 4 Contact force as a function of time over the left quarter of the interface for the 100 Hz to 160 Hz sweep.

To understand the evolution of the contact pressure during resonance, a second set of experiments were conducted in which the excitation frequency was swept from 123 Hz to 125 Hz at a rate of 0.05 Hz/s. Three different excitation amplitudes were used: 1 N, 2 N, and 3 N (denoted as low, medium, and high in what follows).

As before, a significant variation in the contact area is observed in the measurements for all three excitation amplitudes (Fig. 5 for low, Fig. 6 for medium, and Fig. 7 for high). As the excitation amplitude is increased from low to high, the maximum contact area changes from 0.3 in^2 to 0.7 in^2 at resonance (approximately 15 seconds), with a minimum contact area of 0 in^2 in all cases.

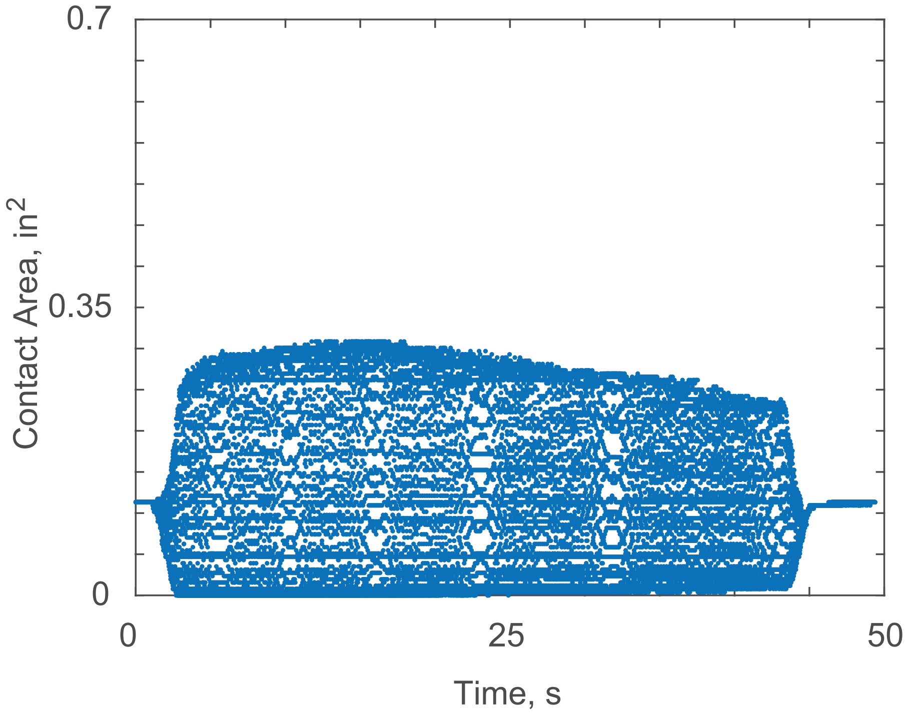

Fig. 5 Contact area as a function of time over the left quarter of the interface for the 123 Hz to 125 Hz sweep at a low excitation amplitude.

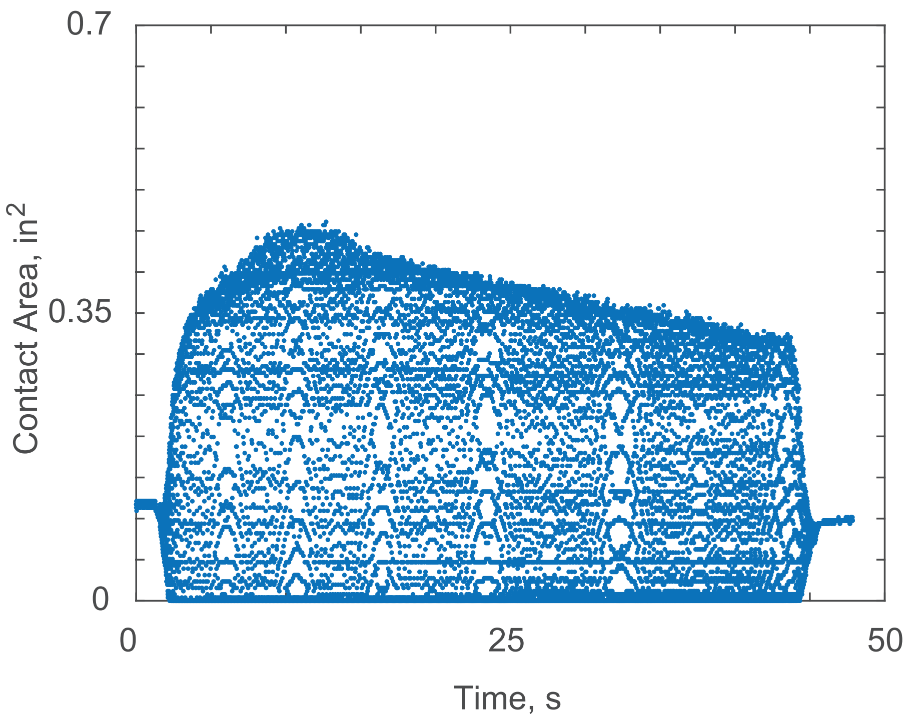

Fig. 6 Contact area as a function of time over the left quarter of the interface for the 123 Hz to 125 Hz sweep at a medium excitation amplitude.

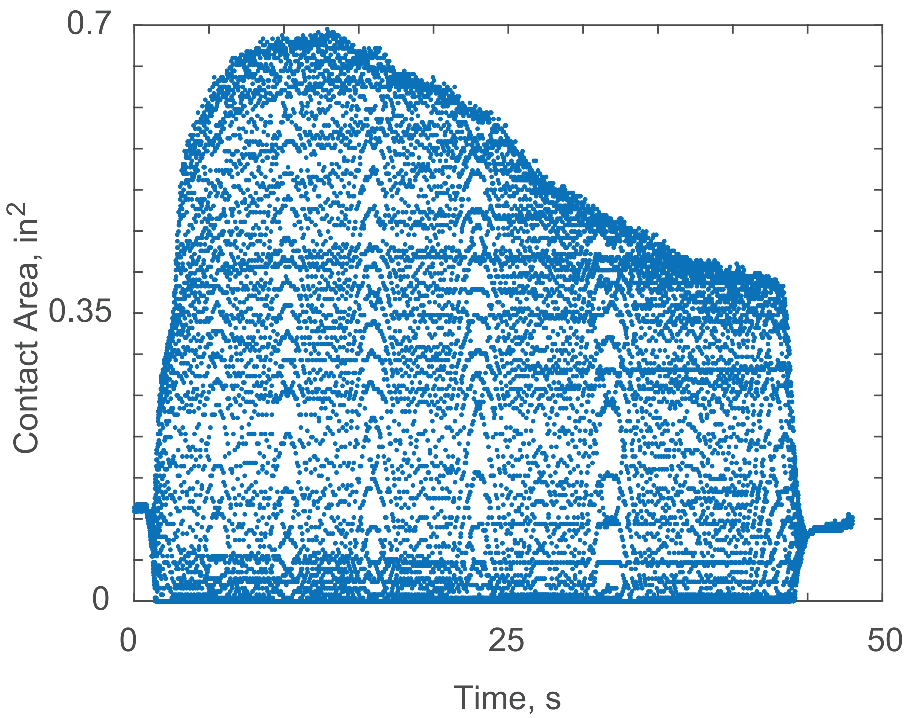

Fig. 7 Contact area as a function of time over the left quarter of the interface for the 123 Hz to 125 Hz sweep at a high excitation amplitude.

Likewise, the peak contact forces (Fig. 8 for low, Fig. 9 for medium, and Fig. 10 for high) are observed to vary from 50 lbs for the low excitation force to 84 lbs for the high excitation force. Both before and after the forced excitation, the contact forces are measured as approximately 18 lbs. Thus, significant variations are observed in the specific conditions of the contact interface during dynamic excitation near resonance, and the contact area is significantly different than the static measurement of the contact area.

To further visualize the evolution of the contact interface during dynamic excitation near resonance, Figs. 11, 12, and 13 (for the low, medium, and high excitations respectively), show the two-dimensional contact pressure maps at four different phases during a period of excitation. The coordinate system is setup such that the left hand side of the plots are the edge of the contact pressure film closest to the middle bolt hole, and the right hand side is the edge of the contact pressure film closest to the shaker. The contact pressure (and correspondingly contact area) is observed to be zero at one point in time for all three excitation amplitudes (Figs. 11(a), 12(a), and 13(a)). As the phase increases, the interface is observed to come into contact around the unused bolt hole (as evident by the dark circular region in Fig. 13(d)). Due to the asymmetric loading of the interface (as a result of the particular experimental setup), the lower

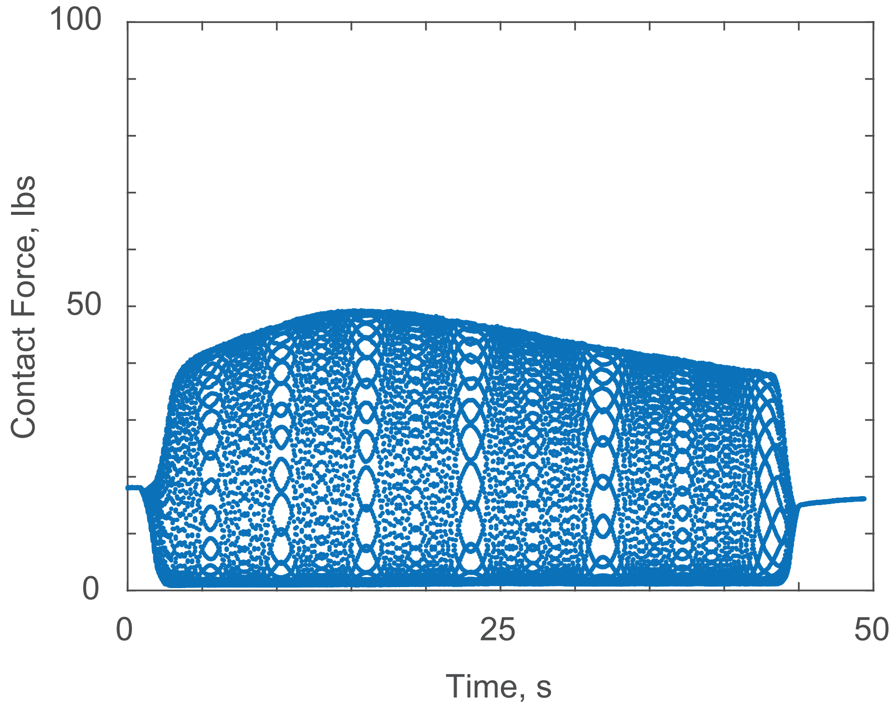

Fig. 8 Contact force as a function of time over the left quarter of the interface for the 123 Hz to 125 Hz sweep at a low excitation amplitude.

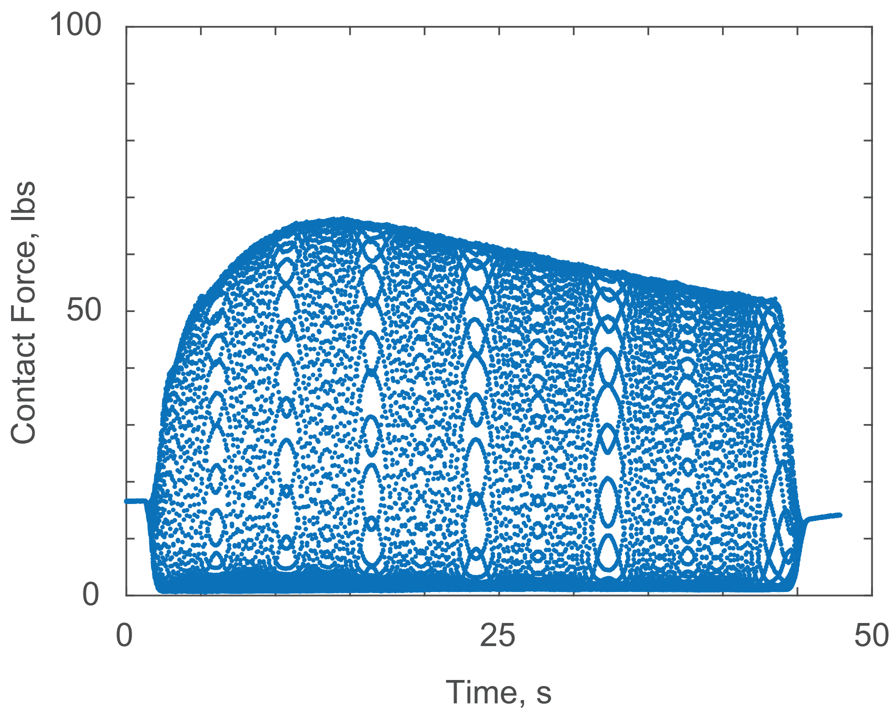

Fig. 9 Contact force as a function of time over the left quarter of the interface for the 123 Hz to 125 Hz sweep at a medium excitation amplitude.

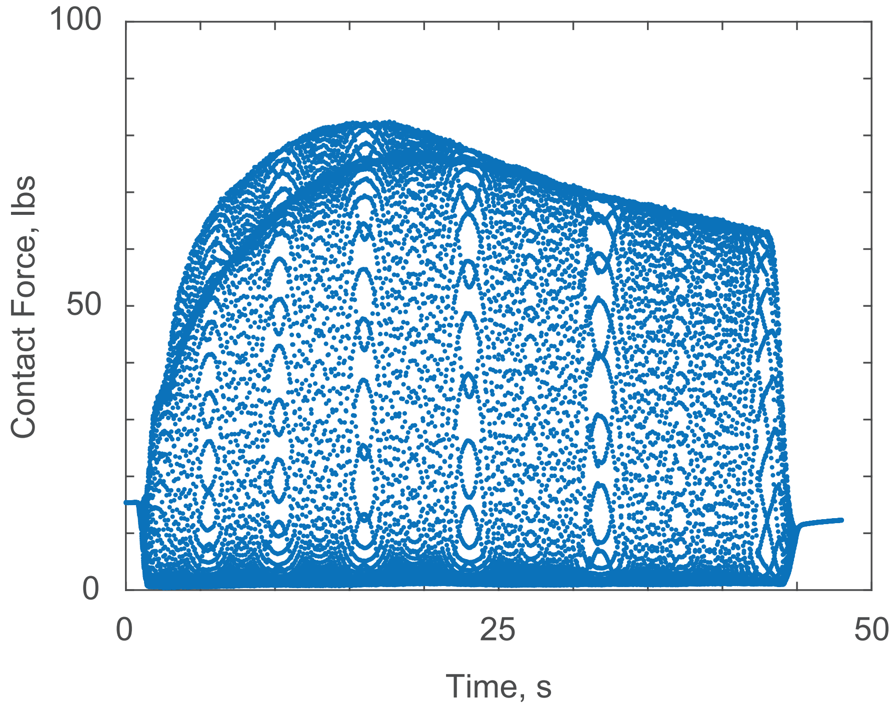

Fig. 10 Contact force as a function of time over the left quarter of the interface for the 123 Hz to 125 Hz sweep at a high excitation amplitude.

corner of the contact pressure film never is fully engaged. For both the low (Fig. 11) and medium (Fig. 12) excitation amplitudes, the interfacial contact is never observed to fully encircle the bolt hole.

4 Discussion and Conclusions

As has previously been observed in numerical studies (Flicek et al. 2016), this research experimentally confirms that the contact patch evolves during dynamic excitation. While several caveats exist, the extent of the contact patch in the present research is observed to change by over an inch (note that the contact pressure sensor is only one inch in width). For larger bolt torques, of course, the magnitude of the contact area change is expected to decrease; nonetheless, this series of experiments shows that the interface cannot be assumed to be static during dynamic excitation as had been previously assumed. Instead, models of jointed structures must be able to capture the evolution of the contact patch during dynamic excitation. Further, as the energy dissipated in an interface is dominated by the regions away from the bolts where contact pressure is lowest (Goyder, Ind, and Brown 2013; Goyder, Ind, and Brown 2014; Goyder, Ind, and Brown 2015), it may be imperative to model the extent of these regions accurately.

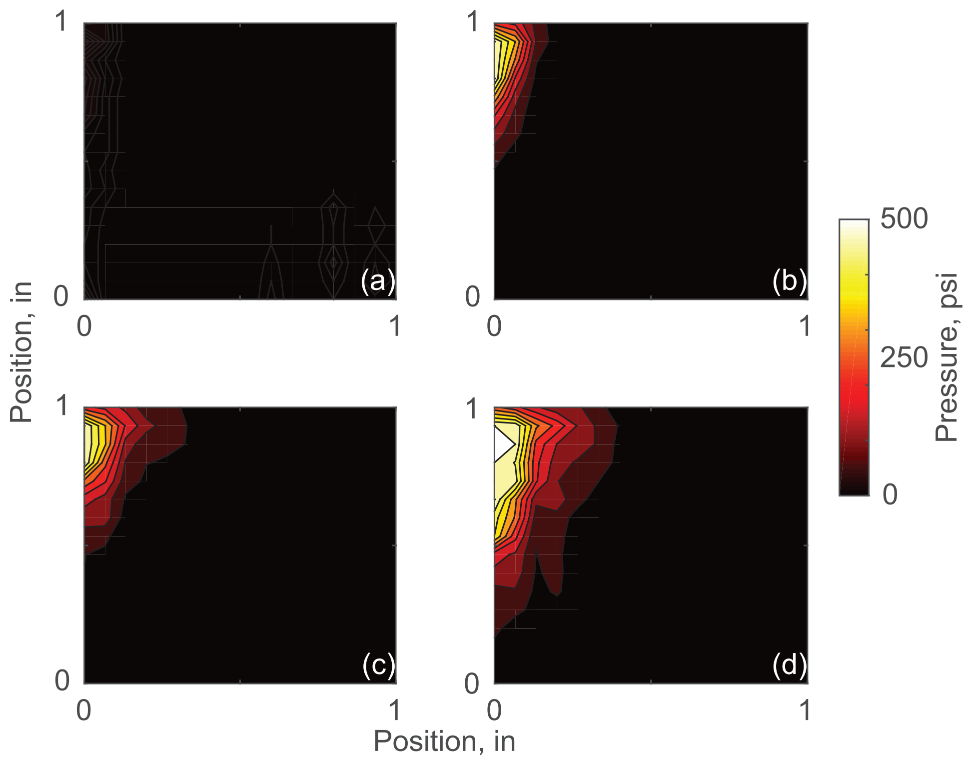

Fig. 11 Contact pressure at four different phases during an excitation of 124 Hz at a low excitation amplitude.

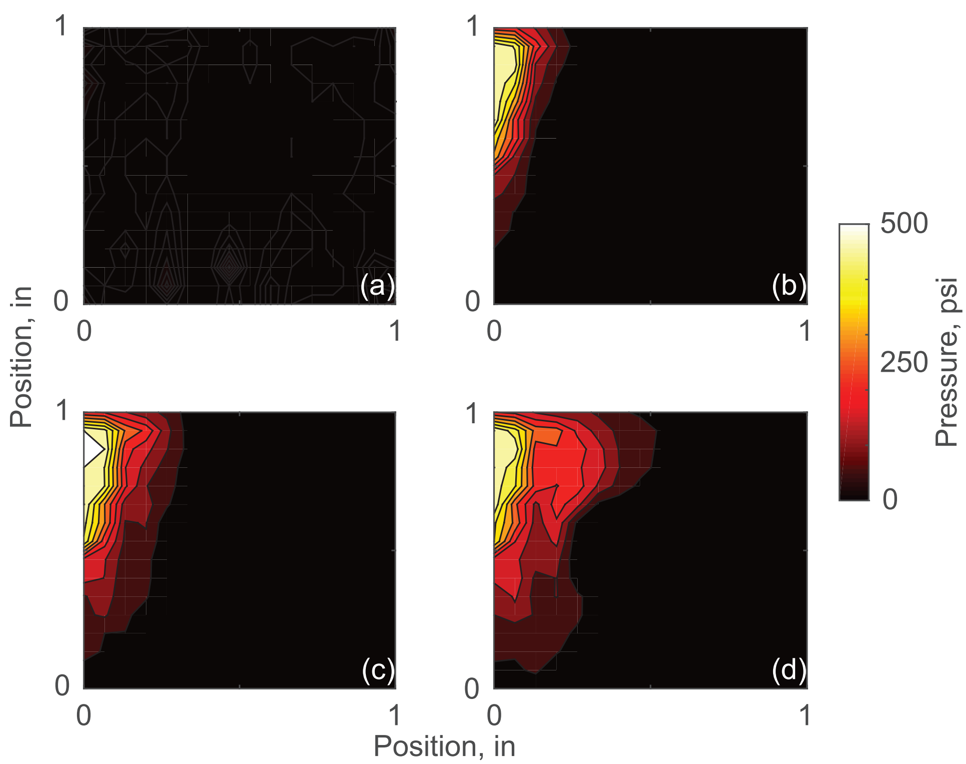

Fig. 12 Contact pressure at four different phases during an excitation of 124 Hz at a medium excitation amplitude.

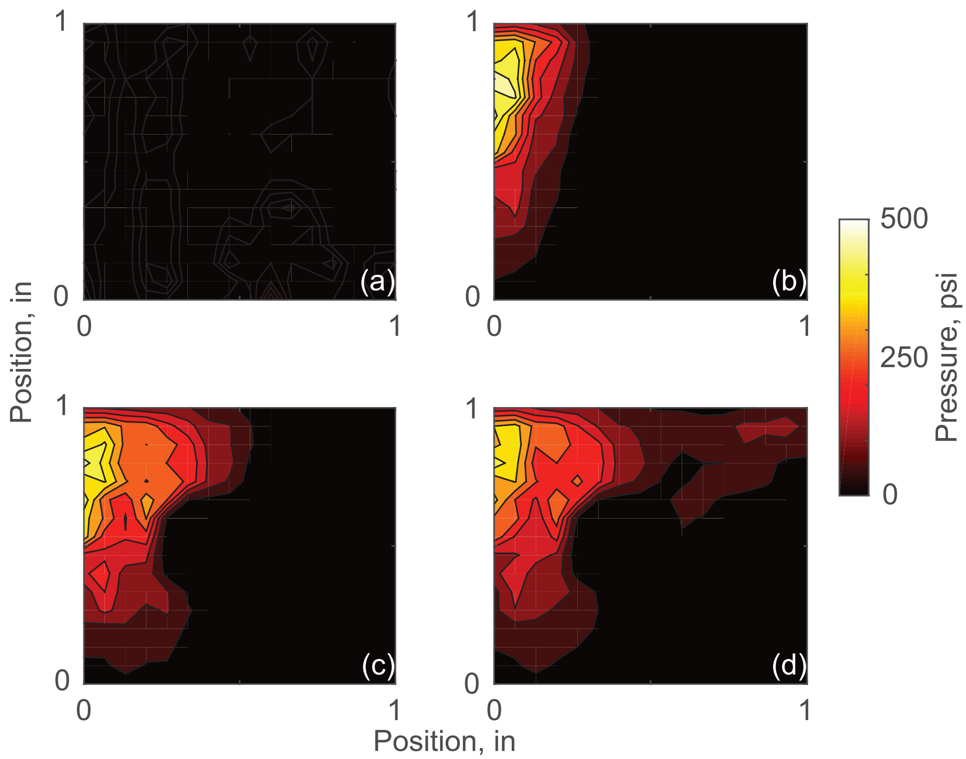

Fig. 13 Contact pressure at four different phases during an excitation of 124 Hz at a high excitation amplitude.

When coupled with the findings of the numerical study of (Lacayo et al. 2017), in which it was shown that better agreement between experiments and models could be achieved by allowing the contact patch to evolve during dynamic excitation, there is, perhaps, a significant and far-reaching ramification: interface models must be improved to capture the local kinematics of contact. This conclusion is somewhat contrary to one of the main approaches for modeling jointed structures, namely the typical manner in which Iwan elements are employed (Segalman 2005; Segalman et al. 2009; Brake 2017). Typically, Iwan elements are used to represent an entire interface, which necessitates that the local kinematics of an interface be regularized to a single (or a small number of) contact patches. This regularization, though, has the potential to go too far and neglect effects such as the evolution of the contact patch during excitation. The advantage of this modeling approach is a significant reduction in the number of degrees of freedom used to represent the interface of a jointed structure. Other methods that are able to incorporate the evolution of the contact patch require orders of magnitude more degrees of freedom in the contact patch than the Iwan modeling approach (Lacayo et al. 2017).

Future work, therefore, must further study the importance of capturing the local kinematics in modeling jointed structures. If it is further confirmed that the modeling of the local kinematics are essential for *predicting* the response of a jointed structure, then a compromise is needed between the different numerical approaches – one where the local kinematics are able to be preserved while reducing the total number of degrees of freedom necessary to represent them accurately. One potential avenue may be to use multiple contact patches defined over an interface (such as in (Lacayo et al. 2017), but perhaps to a greater extent) over which both an Iwan model is defined for the tangential forces and a normal contact model is defined (unlike in (Lacayo et al. 2017)) to capture the local kinematics. A second potential avenue may require a fundamentally different approach from Iwan elements altogether, which requires novel constitutive modeling insights.

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