**Supplementary file**

# Multi-scale investigation on the interaction mechanism of thermosensitive adhesive resin with bridging materials: Toward stable plugging layers in fractured formations

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**Appendix A: Control group: Force chain evolution of monodisperse PMMA**

The structural evolution of force chains within the monodisperse PMMA assembly exhibits a characteristic multi-stage response, as illustrated in Fig. S1. In the unloaded state (Fig. S1(a)), the internal stress distribution is uniform, and no discernible force chain network is observed, indicating mechanical equilibrium. After a 30 kg vertical load is applied, a localized force chain network initiates beneath the loading point and propagates along the vertical axis. Consistent with contact mechanics theory, this localized loading induces stress concentration at interparticle contacts, which manifests as the nucleation of vertical force chains as shown in Fig. S1(b) (Li et al., 2018). Subsequently, as the horizontal load is incrementally increased from 10 to 80 kg (Figs. S1(c)-S1(f)), the contact density within the granular assembly rises, enhancing the efficiency of stress transmission. Consequently, a horizontal force chain network progressively develops and becomes the dominant load-bearing structure. Concurrently, the initial vertical force chain network undergoes compression and distortion, leading to tighter interparticle compaction and stress redistribution in the vertical plane (Wang et al., 2016).

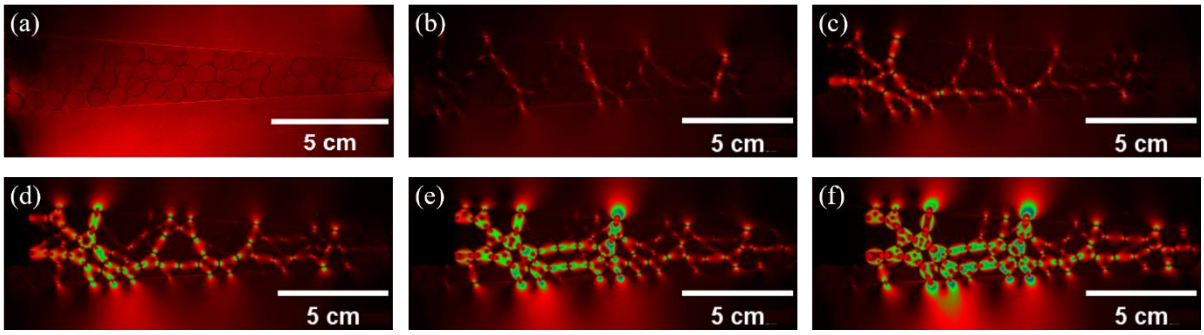


**Fig. S1**. Schematic diagram of mesoscopic force chain structure evolution during single-particle-size pressurization of PMMA material: (a) Initial state, (b) vertical pressurization of 30 kg, (c-f) horizontal pressurization of 20 kg, 40 kg, 60 kg, and 80 kg, respectively.

**Appendix B: Experimental group: Monodisperse PMMA with Resin Adhesive 1**

The evolution of isochromatic fringe patterns for the PMMA system modified with Resin Adhesive-1 is presented in Fig. S2. In the initial unloaded state, the assembly exhibits a relatively uniform stress distribution. However, after a 30 kg vertical load is applied, the force chain network distorts markedly and evolves into a tortuous, buckled vertical path. This pattern indicates strong stress localization and the absence of a distributed load sharing skeleton. As horizontal loading increases, incipient horizontal force chain segments appear but fail to merge into a stable, continuous framework. Instead, the bridging structure degrades rapidly, and macroscopic particle slip occurs. This instability suggests that Resin Adhesive-1 modifies the surface tribology of the PMMA particles, thereby reducing both interparticle friction and particle wall friction. Consequently, this adhesive behaves primarily as a lubricant, which impedes rather than promotes the formation of a robust plugging zone.

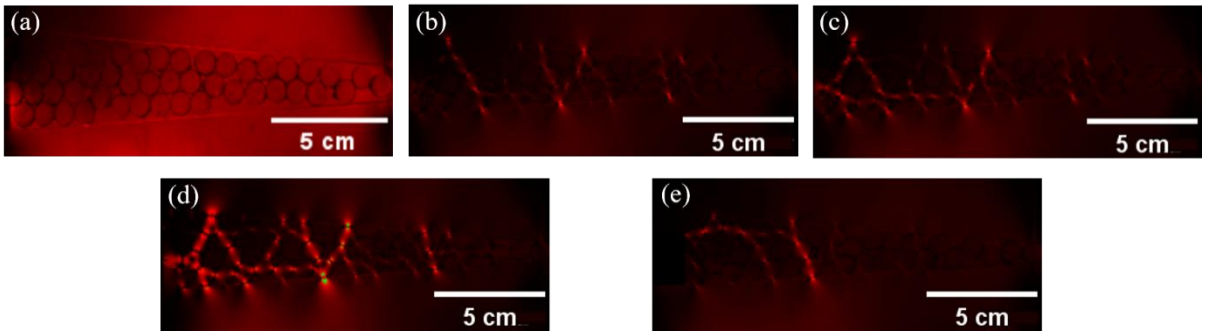


**Fig. S2**. Schematic diagram of mesoscopic force chain structure evolution during pressurization of single-particle-size PMMA + Resin Adhesive-1: (a) Initial state, (b) vertical pressurization of 30 kg, (c) horizontal pressurization of 10 kg, (d) horizontal pressurization of 20 kg, and (e) pressure limit.

**Appendix C: Experimental group: Monodisperse PMMA with Resin Adhesive 2**

The photoelastic response of the PMMA assembly modified with Resin Adhesive-2 under varying loads is depicted in Fig. S3. Compared with the control and Resin Adhesive-1 scenarios, Resin Adhesive-2 enhances the mechanical stability of the granular assembly under compression, effectively mitigating macroscopic particle slip. The resulting force chain network is characterized by higher density and improved homogeneity relative to the control group. Serrated fringes emerge and the force chain field becomes more uniformly distributed, suggesting that the interfacial layer undergoes load-dependent deformation rather than remaining mechanically inactive. The serrated fringe patterns, attributed to the intrinsic photoelasticity of the adhesive layer, indicate that the resin phase actively participates in load transmission and facilitates stress redistribution within the composite particulate assembly. This behavior is consistent with a viscoelastic interface capable of accommodating deformation and maintaining stable stress transfer pathways during horizontal compression (Kyriazis et al., 2021).

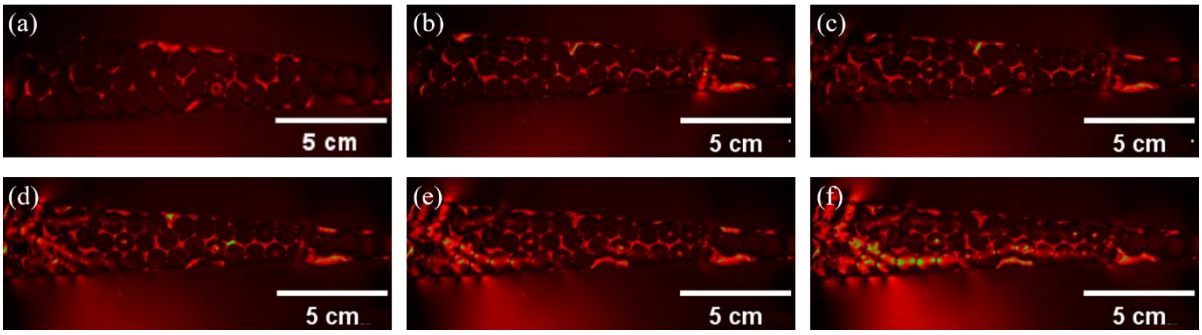


**Fig. S3**. Schematic diagram of mesoscopic force chain structure evolution during pressurization of single-particle-size PMMA + Resin Adhesive-2: (a) Initial state, (b) vertical pressurization of 30 kg, (c-f) horizontal pressurization of 20 kg, 40 kg, 60 kg, and 80 kg, respectively.

**Appendix D: TSAR effects on force chain structure across photoelastic material types**

The evolution of force chain topology across different photoelastic surrogates (PMMA, PC, and PVC) under varying load conditions is depicted in Fig. S4. After the initial 30 kg vertical load is applied, the primary force chain network in all resin-free assemblies exhibits a distinct vertical orientation. As horizontal loading increases, localized stress concentrations emerge within the PMMA and PVC assemblies, which facilitate the formation of high-strength bridging structures. Comparative analysis indicates that the equivalent plugging pressure capacity of PMMA and PVC surrogates is superior to that of PC. However, the PVC assembly exhibits significant compressive deformation and macroscopic slip at the fracture tip during horizontal pressurization, which indicates that its frictional characteristics and mechanical stability are suboptimal for this application. The structural evolution of the force chain network in the TSAR composite systems is depicted (Fig. S5). Under the initial 30 kg vertical load, the primary force chain retains a predominantly vertical distribution. Compared with the resin-free controls, the composites show lower peak stress intensities and fewer isolated high-stress chains. As horizontal load increases, the force chain network in all composite systems expands laterally, indicating more uniform propagation. Although the peak stress intensity of the main force chain is reduced relative to the rigid controls, the total number of particles participating in the load-bearing skeleton increases significantly. This shift supports a transition from localized, high-intensity bridging to a distributed, cooperative load-bearing mechanism. The reduction in main chain intensity coupled with the increased fraction of particles incorporated into the load-bearing skeleton improves network uniformity and global stability (Nina et al., 2020).

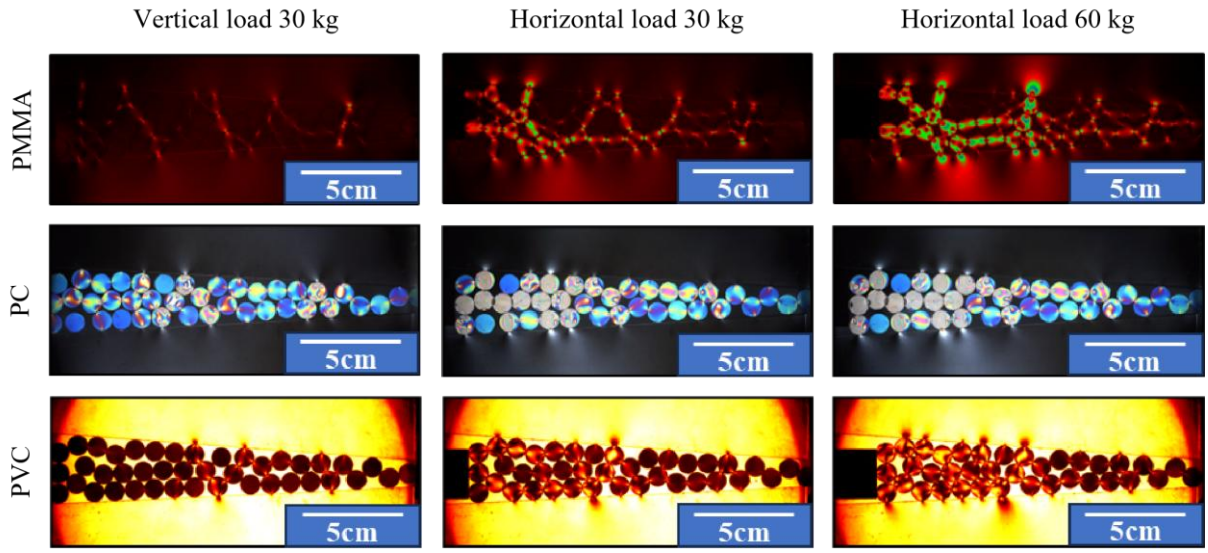


**Fig. S4**. Schematic diagram of mesoscopic force chain structure evolution during pressurization of different types of photoelastic materials.

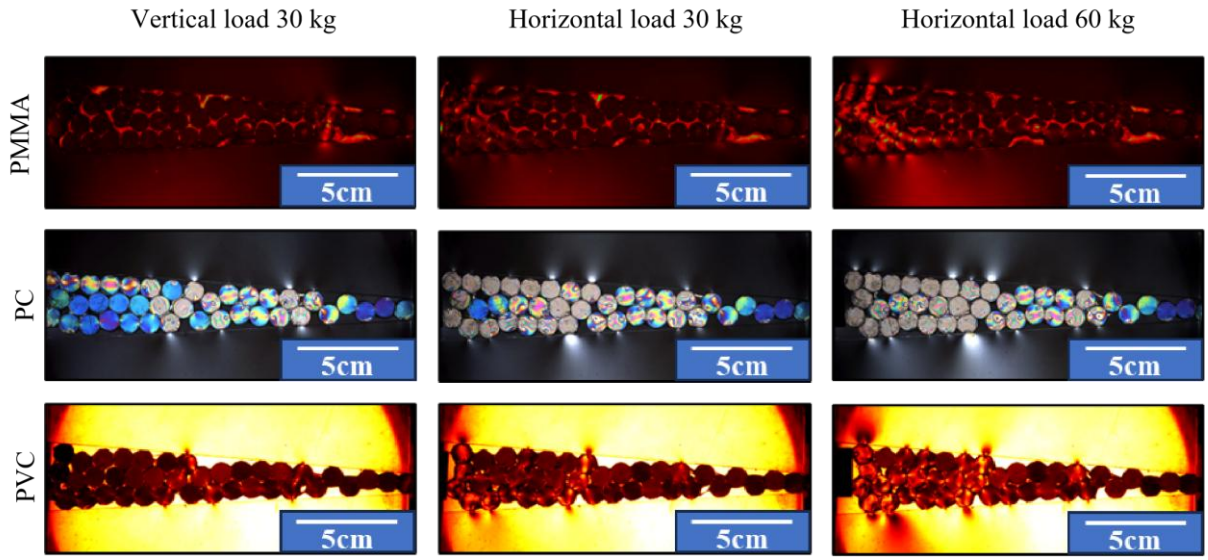


**Fig. S5**. Schematic diagram of mesoscopic force chain structure evolution during pressurization of systems composed of different types of photoelastic materials + Resin Adhesive-2.

**Appendix E: TSAR effects on force chain structure across particle sizes**

The evolution of force chain topology within assemblies of varying particle sizes (5 mm, 8 mm, 10 mm, and polydisperse mixtures) under progressive loading is illustrated in Fig. S6. Across all particle diameters, the force chain network becomes increasingly complex as pressurization progresses, and local stress concentrations intensify. Clear size-dependent responses are observed. The fine-grained assembly (5 mm) progressively develops a compact and ordered force chain network. By contrast, the coarse-grained assembly (10 mm) and the polydisperse system exhibit more pronounced stress localization and a more heterogeneous force chain orientation. These differences are consistent with coordination-number effects. Smaller particles produce a higher density of contact points, which promote more uniform stress distribution, whereas larger particles, with fewer contact points and greater relative displacement, are more prone to severe stress concentration at contact interfaces. In the polydisperse system, fine particles partially occupy the interstitial voids between coarse particles, alter contact modes, and create secondary stress-transfer pathways, which enhance network stability.

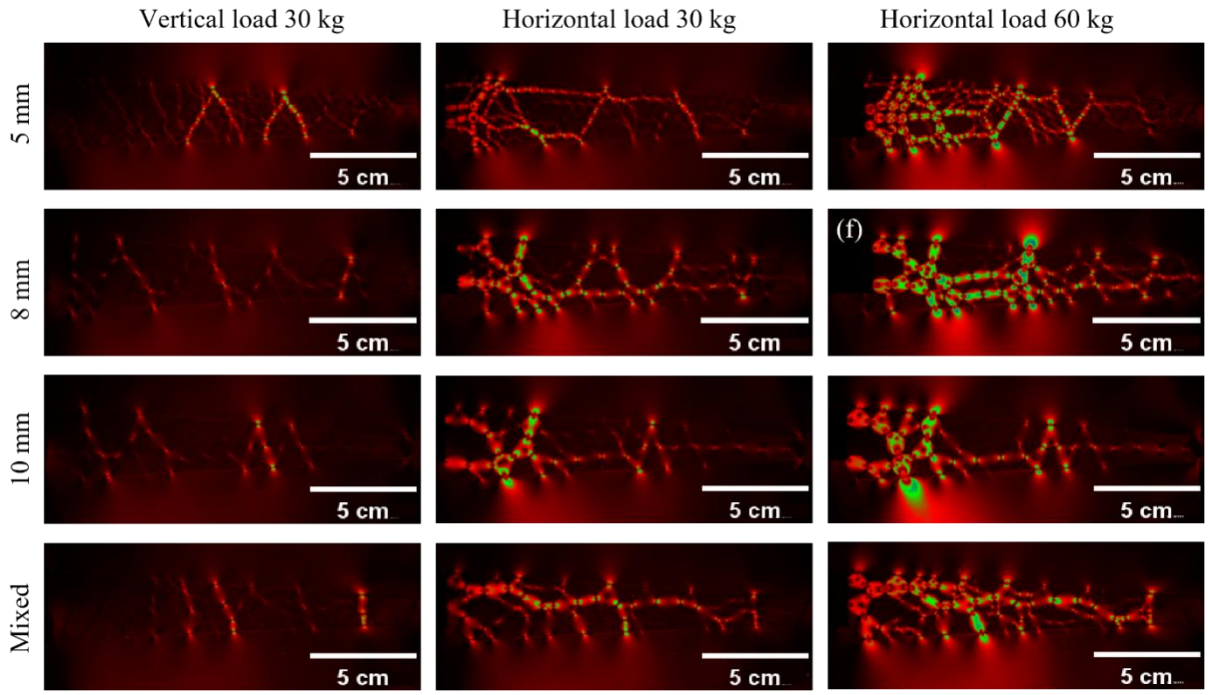


**Fig. S6**. Schematic diagram of mesoscopic force chain structure evolution during pressurization of PMMA with different particle sizes.

The photoelastic response of these assemblies after modification with Resin Adhesive-2 is shown (Fig. S7). The resin-induced enhancement in effective contact area and stress homogenization increases with particle size. For fine-grained assemblies, where the native contact density is already high, the resin provides only marginal additional stress dispersion. As particle size increases, the resin plays a critical role in alleviating the severe stress concentrations intrinsic to coarse-grained packs. By filling interstitial voids and increasing the effective contact area, the resin converts point contacts into area contacts. In the polydisperse system, the resin acts as a viscoelastic bridge, mitigating stiffness mismatch between heterogeneous particles and facilitating more uniform load transfer.

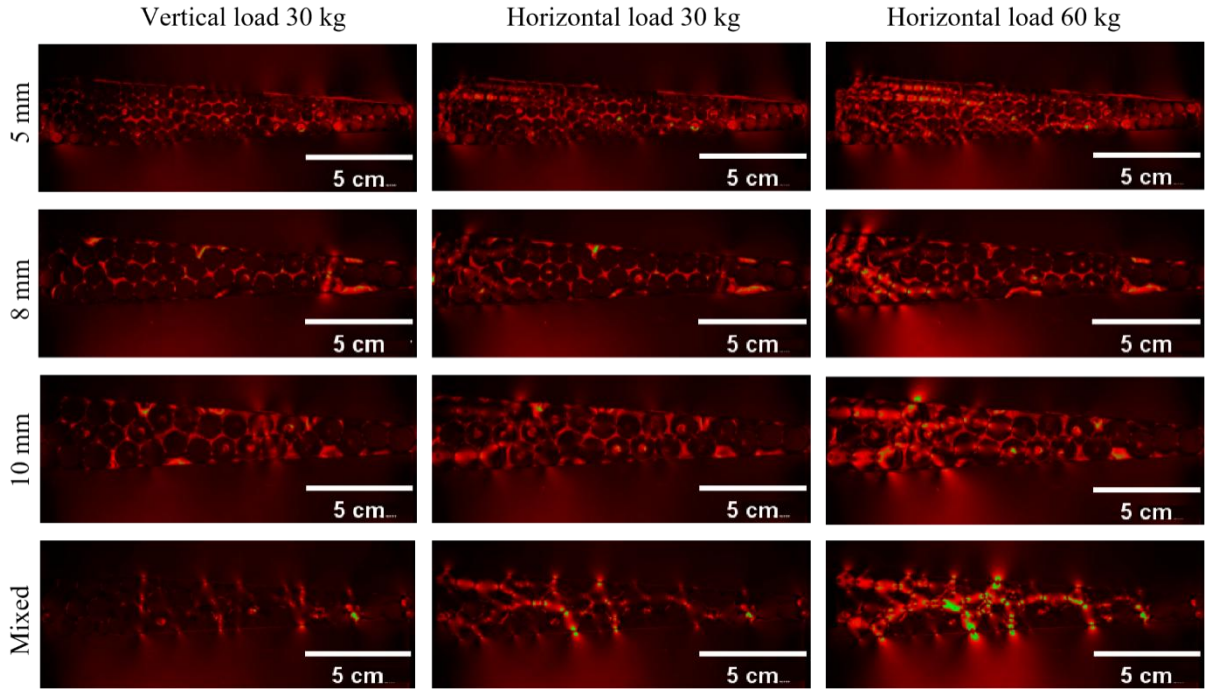


**Fig. S7**. Schematic diagram of mesoscopic force chain structure evolution during pressurization of PMMA + Resin Adhesive-2 systems with different particle sizes.

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