Chapter 3
Shear Thickening Fluid Integrated Sandwich Structures for Vibration Isolation

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3.1 Shear Thickening Fluid

Shear thickening fluid (STF) is a type of non-Newtonian material in which the viscosity rises as a function of shear rate or shear stress at a key parameter range as shown in Fig. 3.1. In many concentrated suspensions, a particularly disturbing version defined as shear thickening happens. When combined slowly, these suspensions are like a thin liquid; however, it is very thick like a solid when churned faster and then thin again when the loading is removed from the liquid [1, 2]. STF has been the subject of study throughout time to comprehend its rheological behavior and make use of it in engineering applications. Shear thickening was initially identified as a challenge in industrial processes like coating and mixing because it jams in tight spaces and overloads mixers, consequently reducing the process rate. However, more recently, smart materials and structures have been developed using the special property of these fluids. The rheology of an STF is determined by particle size, particle shape, size distribution, particle density, charge, particle roughness, and, in

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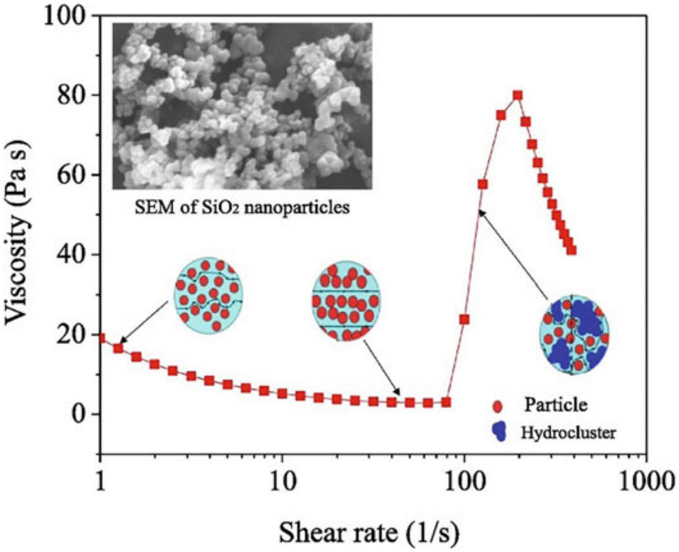


Fig. 3.1 Rheological properties of STF [6]. (Reprinted by permission from Elsevier)

certain situations, chemical interaction between the particle surface and carrier fluid [3, 4]. The initiation of reversible shear thickening at critical stress is affected by particle size, concentration, polydispersity, and interparticle interactions of dispersion [5].

Hence, STF, a soft material with intelligent properties, is more resistant to external force than a liquid and thereby displays variable properties unlike solids. As a result, STF has several application possibilities in the fields of surface polishing [7], human body protection [8–10], shock absorption [11–13], energy suppression [14], and vibration damping [15–18] in engineering structures. Although extensive studies have been conducted in recent years for the use of STF in engineering structures, the potential of these materials in integrating with new systems and transforming them into intelligent structures can still be considered, and their capacities can be studied.

3.2 Sandwich Structures

Sandwich structured composites are a specific type of composite materials with characteristics including low weight, high stiffness, and high strength. Sandwich structures are created by laminating two lightweight, moderately thick cores to two strong and rigid laminated facesheets [19]. The sandwich is like an endless I-beam in that when it bends, the flanges carry compression and tension loads in-plane (as do the sandwich facesheets), while the web bears shear loads (as does the structural

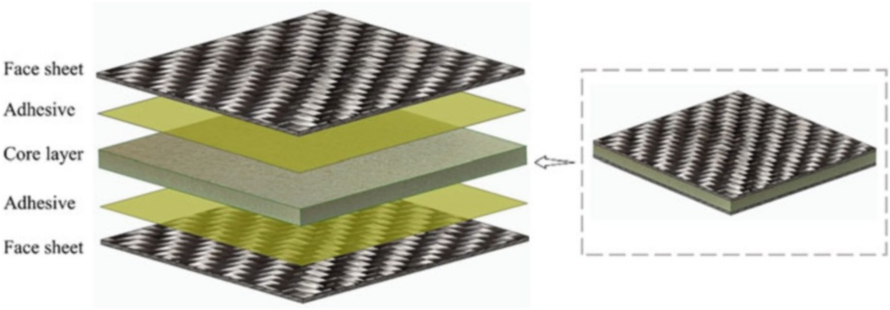


Fig. 3.2 Components in a conventional sandwich structure

sandwich core). Like a conventional I-beam, the structure becomes proportionally stiffer the farther away the flanges (facesheets) are from one another. The same result is achieved by a thicker core, but it also offers a low overall density, leading to a high stiffness-to-weight ratio. The potential for weight savings from utilizing a sandwich is demonstrated by a comparison of a steel panel and a composite sandwich panel. When the same deflection requirements are used, the weight reduction with sandwich design is close to 90% [20]. Thermal insulation, acoustic dampening, buoyancy, noncorrosiveness, and enhanced impact resistance are further advantages of sandwich structures. The stiffness of any beam or panel is inversely proportional to its thickness. The little weight penalty and higher yields in thickness are two significant differences between designs using traditional materials and those using a sandwich composite solution [21, 22]. A typical sandwich is composed of upper and lower facesheets with a significantly thicker core in between as shown in Fig. 3.2.

The tensile and compressive stresses in the sandwich structures are carried by the facesheets. Because the local flexural stiffness is so tiny, it is frequently neglected. Facesheets are commonly produced of conventional materials such as steel, stainless steel, and aluminum. In several applications, fiber- or glass-reinforced polymers can also be used as face materials. These materials are simple to use. Reinforced plastics may be designed to meet a variety of requirements such as anisotropic mechanical qualities, design freedom, high surface polish, and so on. Local pressure is also carried by the faces. Facesheets have to be measured for the shear forces related to them when the local pressure is high [23].

The role of core material is to hold the thin facesheets and keep them in relative position to each other so that they do not bend or deform inward or externally. To do this, the core material needs to possess several critical qualities. It needs to be stiff enough to maintain a continuous spacing between the faces. It must also be shear stiff enough to prevent the facesheets from sliding over one other. The shear stiffness pushes the facesheets to work together. If the shear strength of the core is low, the facesheets will not cooperate, and the sandwich will decrease rigidity [24]. To keep the facesheets and the core layer interacting, the adhesive between them has to be capable of transferring shear forces between them. Moreover, the adhesive has to withstand the shear and tensile loads. The pressures on the joints are difficult to describe. The adhesive should be able to withstand the same shear stress as the core, according to a simple criterion [25].

3.3 Shear Thickening Fluid Integrated Sandwich Structures for Vibration Isolation

Vibration is generally an undesired phenomenon because of its negative effects on structural stability, position control, material performance, fatigue life, and noise reduction. Vibration dampening has been the subject of specific study to suppress vibrations that impact structures. It is preferable to increase structural stiffness and damping capability in vibration damping investigations. Materials should generally possess viscoelastic properties. For this reason, rubber and plastics are widely used in vibration damping applications. Vibrational energy is attenuated by heat loss because of the viscoelastic characteristics in the materials. In addition to viscoelasticity, microstructural defects in metal alloys, such as dislocations, grain boundaries, and secondary phases, are advantageous for vibration damping purposes. Zhang et al. [26] created a single-rod STF damper for the use of STF in the field of vibration control and supplied the hysteretic curve of the damping force versus displacement when the loading frequency varied. Due to the shear thickening mechanism of STF to offer a damper with a larger stiffness or damping, the curve demonstrates that the damper's capability to dissipate energy under high dynamic loading greatly exceeds that under low dynamic loading. To prevent the negative impacts of single-ended dampers on the thickening performance of STF, Zhou et al. [27] presented an STF double-rod damper. Higher damping or shock resistance is displayed by the damper packed with a denser STF because it dissipates more energy during each cycle. Zhao et al. [28] investigated the damping force vs. displacement and the damping force vs. velocity curve to analyze the dynamic performance of an STF damper. The maximum damping force in the STF damper, however, was less than 30 N because of the extremely constrained physical characteristics of the device. Given the scale effect of the test findings, the damper's applicability in vibration control is restricted. Comprehensive experimental research of STF dampers was carried out by Yeh et al. [29]. Even though the study showed how different harmonic loads affected the damp-velocity curve's hysteretic performance, only three sets of damp-velocity curve data were produced under low displacement and low loading frequency circumstances. Fischer et al. [30] created a sandwich beam structure based on STF to meet the goal of controlling the structural stiffness and damping under dynamic deformation. The stiffness and damping characteristics of the sandwich beam varied simultaneously as the loading amplitude changed. Due to the shear thickening effect in the core layer, the stiffness of the sandwich beam considerably reduced as the loading amplitude increased.

3.4 Damping and Vibration Isolation

Vibration is a frequently occurring phenomenon. Everything vibrates; it is only the degree of the vibration and its impact on machines, systems, and the environment that are of importance to humankind. Vibration is described as a particle's time-dependent movement around its equilibrium state. The dynamic (time-dependent) displacement is either uniform (harmonic) or nonuniform in timeframe (nonharmonic). The distinction between oscillation and vibration is that in oscillation, matter travels repeatedly about an equilibrium point without deforming the body, but in vibration, periodic deformation of a structure is also involved. Another effect of vibrations is a wave known as "sound," which is merely a mechanical pressure wave that may travel through a variety of media including gas, liquid, and solid. Within the range of 16–20,000 Hz, airborne sounds are detectable to the human ear. Vehicle horns, vocal cords, and all musical instruments are typical illustrations of vibration produced sound.

The dissipation of vibrational energy through time and distance in solid mediums and structures is known as damping. Like how sound is absorbed by air, damping happens wherever there is friction that lessens motion and disperses energy. The loss factor or ratio between the energy dissipated and the energy still present in the system throughout each cycle is referred to as each material's damping capability. In construction, dampening is crucial for preventing vibrations and maintaining the security and comfort of infrastructure and buildings. Friction is an instance of a dynamic damping system. Another example is the resistance that an automobile faces. The air resistance and the rolling friction of its tires are that cause the resistance. Viscous damping is the damping effect that occurs in liquid situations. Consider rolling a ball with a given amount of initial force on the floor. If there is nothing to stop this movement, the ball will continue to roll eternally. However, the ball eventually comes to rest due to friction between the ground and the ball, which counteracts the ball's movement, causing it to lose speed and eventually come to a stop. Damping is a technique for reducing vibrations and is crucial for the system's safety. When a door or drawer is opened or closed, damping prevents a significant impact, conserving the spring hinges and safeguarding the system. A similar function is served by bridge deck damping devices on a big scale. Assuming that a structure or building is being affected by dynamic energy at a frequency that is like (or close to) its natural frequency, in theory, the overlapping frequencies of the exciting force (disturbing frequency) and natural frequency lead to increasing vibration amplitudes. Various solutions have been researched to prevent resonance effects, and two key measures are included in the vibration isolation concept:

- Changing the natural frequency of the structure, adjusting the load and its distribution, and establishing a suitable gap between the structure's natural frequency and the exciting disturbing frequency. Dynamic loads and wind effects are two examples of incoming dynamic forces that can cause unpleasant frequencies.

- The stability of the structure is ensured even in resonance situations by the addition of dampening properties. When in resonance, it helps with energy loss.

It's a popular misunderstanding that vibration isolation of the structure may be accomplished "simply by adding some rubber" to the system. A resilient component can, however, have the opposite effect and increase displacements if it is introduced without considering the characteristics of the system (environmental atmosphere, temperature, material's rigidity, contact area, material transmissibility, material form factor, excitation frequency, etc.). The performance of an insulation system is defined by its transmissibility, which is the ratio of energy injected into the system to energy exiting the system. The vibration control material is chosen with the system's disruptive frequency in the insulating area in mind. Furthermore, the damping volume of the insulation system will define the system's maximal transmissibility level. The peak value drops as dampening rises.

A structure's dynamic responsiveness and transmissibility are primarily influenced by its mass and stiffness qualities, which are responsible for the energy remaining in the system and, by damping, which affects energy loss in the system. Damping is the least known and most difficult to forecast and quantify of these three properties. Because mass and stiffness can be established using static measures, they are easier to understand and quantify. The transmissibility curves for various damping factors are shown in Fig. 3.3 as functions of the frequency ratio. Using different damping factors of 0.05, 0.1, and 0.15, the decrease in transmissibility beyond $\omega = \sqrt{2}\omega_0$ occurs considerably more quickly with frequency for the low damping factor than it does for the larger damping factor. The system's dampening ability determines how transmissibility is reduced. For example, when a machine is placed on a shock and vibration damping platform apparently constructed of an elastomer, the damping, which is a dynamic viscoelastic loss feature of the elastomer, is highly dependent on the frequency and temperature of the environment. Dampers composed of STF would exhibit similar behavior. As a result, the amount of loss in transmissibility may differ from a theoretical curve derived as shown in Fig. 3.3, because it is assumed in this case that the damping factor is the same over the whole frequency range. The following equation reflects the vibration's amplitude when a machine vibrates because of base excitation with a viscoelastic damping mount:

In the situation of automotive suspension design, Fig. 3.3 might be evaluated to lower vibration intensity. If we can achieve ${}^{\omega}\!/_{\omega_0} \gg 1$ by decreasing the suspension spring stiffness (soft spring) and increasing mass, the natural frequency (ω_0) of the unit is reduced, and the vibration attenuation is improved at the working frequency (ω). Lower stiffness, on the other hand, may increase the likelihood of transverse deflection in a rubber-based mount, resulting in additional vibrations in other directions. A reduced damping factor can also result in a considerable reduction in vibration amplitude beyond resonance. The low damping factor, on the other hand, has two important drawbacks: first, with any extra transient force, which is quite common for automobiles, the natural decay will take a long time, and second, at the resonance frequency, the vehicle may be damaged owing to the excessive amplitude

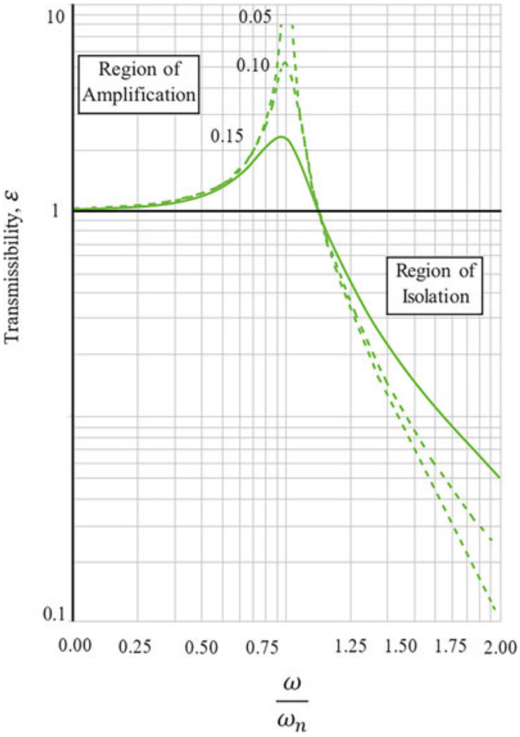


Fig. 3.3 Degree of transmission for a single degree of freedom (SDOF) damped forced vibration with different damping factors (0.05, 0.1, and 0.15)

of vibration. A third issue would be transmitted noise at higher frequencies. As a result, a suspension design is a balanced combination of spring and damper that necessitates an optimal viscoelastic material design. Equation 3.1 reflects the vibration's amplitude when a machine vibrates because of base excitation with a viscoelastic damping mount:

$$u(t) = \frac{\frac{F}{k}}{\sqrt{\left(1 - \frac{\omega^2}{{\omega_n}^2}\right)^2 + 4\xi^2\left(\frac{\omega}{\omega_n}\right)^2}} \tag{3.1}$$

where F/k is the mount's static deflection. This formula compares the amplitude of vibration at each frequency point to the static deflection. The amplitude reduction is affected by two parameters: the frequency ratio and the damping factor. The greater the frequency ratio, the greater the amplitude decrease. However, in the absence of a damper mount, the intensity at resonance ($\omega = \omega_0$) is infinite.

3.5 A Case of Vibration Isolation by an STF Integrated Sandwich Structure

3.5.1 Experimental Details

Using a high-speed homogenizer, fumed silica particles (20 wt% and 40 wt%) were progressively added and distributed in a polyethylene glycol (PEG) pool. To ensure a homogenous and steady dispersion, the mixing procedure was prolonged for an additional hour. The suspensions were maintained at room temperature overnight after the dispersion stage to get the removal of air bubbles. Within 2 hours of the preparation procedure, rheological experiments were conducted with the suspensions.

In the sandwich structures, the core material was a cork agglomerate supplied by Ducork, Inc., which has a density of 170–190 kg/m^3. Cork is a kind of wooden product that is stripped from the outer layer of a cork oak tree. Cork microstructure includes several closed cells. Because the big part of the cork includes air inside the cells, the cork floats on water, which means that it has a very low density. In addition to lightweight properties, cork shows good mechanical properties, and therefore, it can be adapted to energy absorbing and vibration damping systems. Sandwich composites were manufactured by scaling the cork core layers into 50 mm × 50 mm × 10 mm. Two 1.0-mm-thick glass fiber reinforced polymer (GFRP) (fabricated by hand-layup method) sheets were bonded to the cork core layers with powerful double-sided tape adhesive (supplied from Beta Kimya, Turkey). To integrate the fabricated sandwich structure with STFs, 3-mm-wide grooves in the cork core layers machined by a Miller FF 500/BL-CNC (Proxxon, Germany) and filled with STF. Figure 3.4 shows the machined design of the cork core layers for STF injection. Three different designs were considered to show the effect of STF. In Config-1, a neat sandwich structure was considered. In Config-2, the grooves were filled with STF with 20 wt% SiO_2. In Config-3, STF with 40 wt% SiO_2 was injected. Figure 3.5 shows the final form of a sandwich structure.

The study of a system's dynamic characteristics, which are defined apart from the pressures exerted on the system and its reaction, is known as modal analysis. Modal analysis may be used to investigate the vibration properties of mechanical constructions. It converts difficult-to-perceive vibration signals of excitation and response detected on a complex structure into a set of easily predicted modal properties. Structures vibrate or take on mode forms when stimulated at their natural frequencies. Under typical working conditions, a structure will vibrate in a complex combination of all mode configurations. The modal analysis transforms a complex and difficult-to-understand structure into a collection of unconnected single-degree freedom systems. An impact hammer is a specialized measurement tool that creates a short duration of excitation levels by hitting a specified place on the structure. Facesheets and sandwich structure specimens were clamped to a bench clamp and vibrated with a hammer to propagate vibrations on the structures during vibration testing in this study. An accelerometer placed on the opposite face of the impact location was used to assess the structural damping ratio of the specimens. Figure 3.6 shows the experimental setup in the vibration testing.

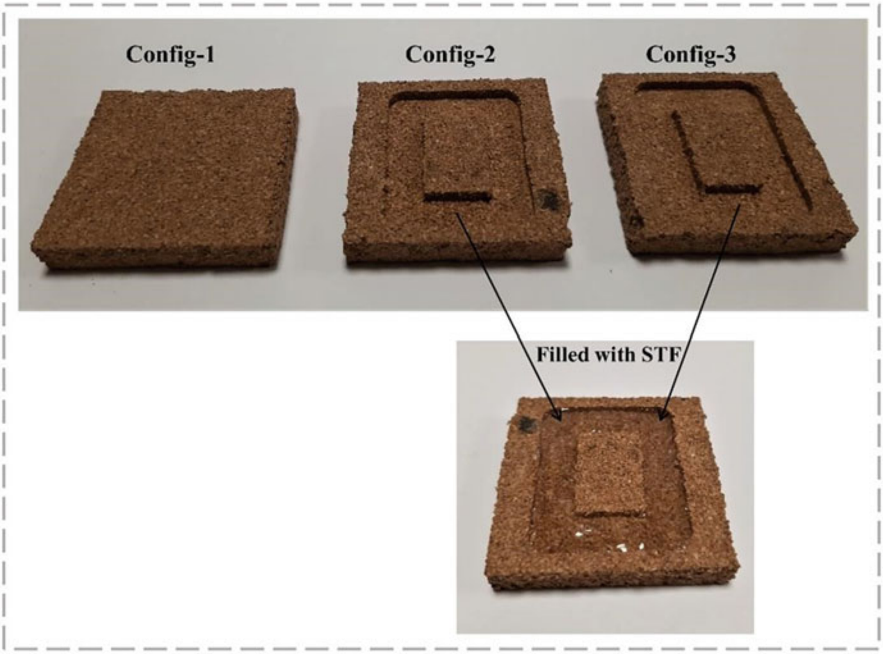
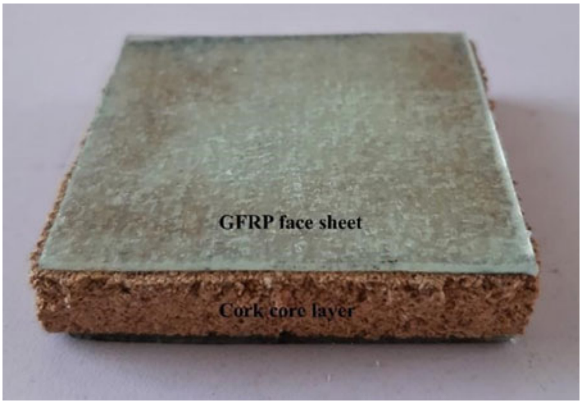


Fig. 3.4 Core layer design of sandwich structures

Fig. 3.5 Fabricated sandwich structure



3.5.2 *Results and Discussion*

Standard parallel plate system was used in the rheological measurements. The distance between the plates was fixed at 1 mm. The shear rates used in the studies ranged from 0 to 1000 s^{-1}. To prevent loading effects, a pre-shear of 1 s^{-1} was applied to the samples for 60 s before the measurements. Figure 3.7 shows the rheological behavior of STFs with 20 wt% and 40 wt% SiO_2.

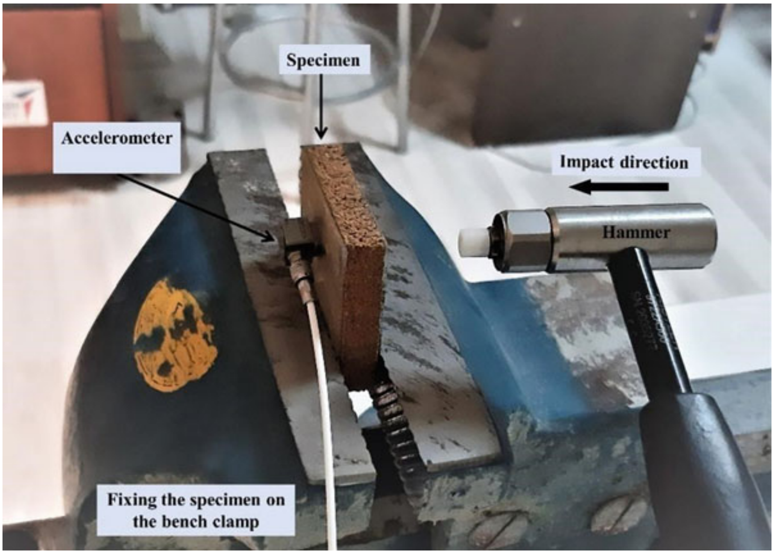


Fig. 3.6 Experimental setup in the vibration testing

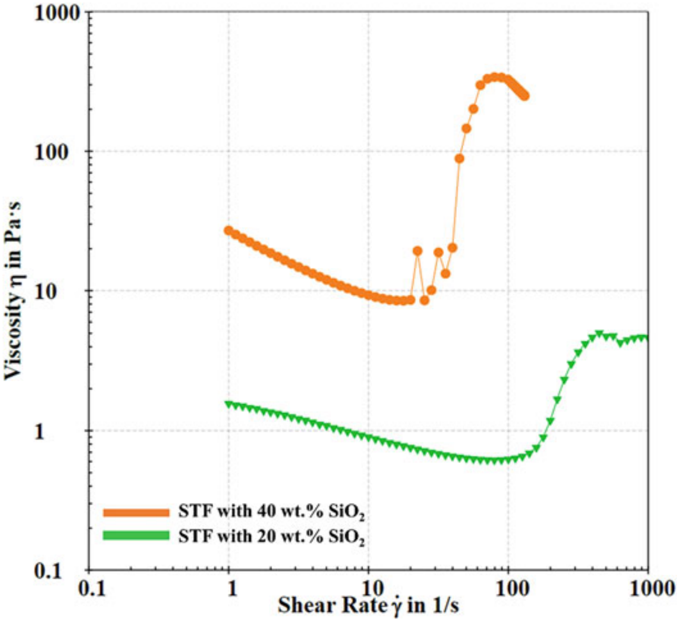


Fig. 3.7 Rheological behavior of STFs with 20 wt% and 40 wt% SiO_2

In Fig. 3.8, frequency response functions are shown for three different configurations. When the configurations are investigated, one or two peaks can be observed. Accordingly, these structures can be modeled as single or double degrees of freedom structures. Modeling these configurations as single degree of freedom reveals that

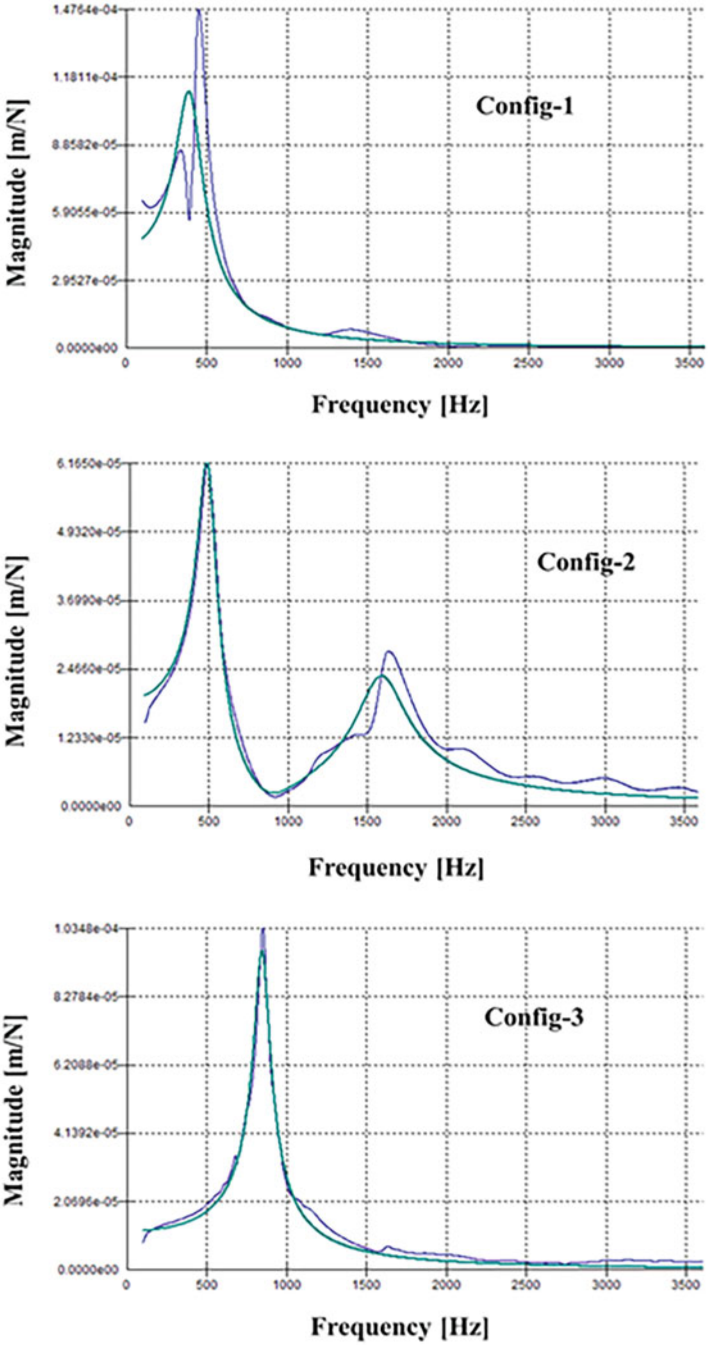


Fig. 3.8 The frequency response function graphs of sandwich structures

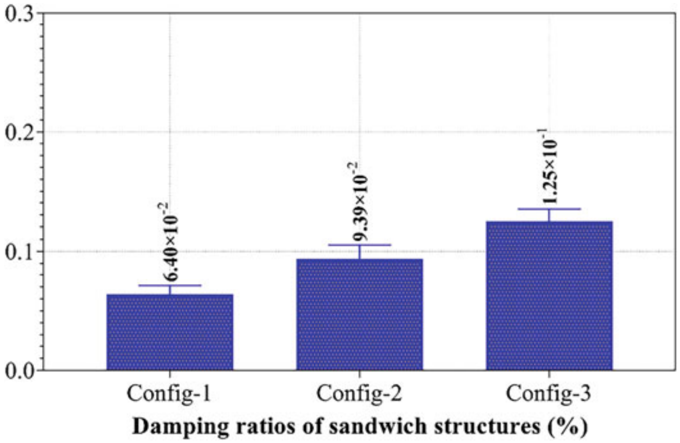


Fig. 3.9 Damping ratios for the sandwich structures

the natural frequency varies between 400 and 800 Hz. In general, the presence of silica can increase the stiffness of a material, which can lead to an increase in the natural frequency of a system. This is because the stiffness of a material determines how much it resists to deformation under loading and a stiffer material will have a higher natural frequency.

Figure 3.9 shows the damping ratios for the three different configurations. The vibration damping ratio is a measure of how effectively a material absorbs and dissipates energy when it is subjected to vibrations. It is defined as the ratio of the energy dissipated in the material to the energy input to the material. Materials with a high damping ratio can absorb and dissipate a greater amount of energy, making them more effective at reducing the amplitude of vibrations. The damping rate is increased by two times or more in the structure with STF and silica. When STFs are used as a damping medium in vibration control applications, they can have a positive effect on the damping ratio of the system. By increasing viscosity under shear stress, STFs can absorb and dissipate more energy, making them more effective at reducing the amplitude of vibrations. Silica can have a positive effect on the vibration damping ratio of a material when it is used as a filler. By increasing the stiffness and reducing the hysteresis of the material, silica can help to reduce the transmission of vibrations through the material and increase its damping ratio.

3.6 Conclusions

STF is used as an intelligent material that responds to high shear loads due to the beneficial attribute of excellent energy dissipation. This chapter investigates the possibility of using STF as a smart fluid with unique rheological properties in vibration damping of sandwich structures. First, an introduction to STF, sandwich structures, and vibration isolation were discussed, and then, as a case study, sandwich structures consisting of GFRP facesheets and cork cores were designed. Two types of STFs (20 wt% and 40 wt% silica contents) with different rheological properties were added to the cork core, and then a hammer-based forced vibration testing was carried out with the sandwich composites. The results of the case study show that adding STF to the cork core significantly increases the damping capability of the sandwich structures. It can be stated that STF is a good candidate material for vibration control applications due to its intelligent properties.

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