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Nano-silica inclusion effects on mechanical and dynamic behavior of fiber reinforced carbon/Kevlar with epoxy resin hybrid composites

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Abstract. The effects of nano-silica (NS) particles inclusion on the tensile, flexural, vibration and damping characteristics of intraply and woven fiber reinforced carbon/Kevlar/epoxy (CKFRE) hybrid composites were experimentally investigated. Test samples were prepared according to ASTM standards for five different weight contents of NS particles (0.5, 1, 1.5, 2.5 and 3 wt%). Experimental modal analysis was performed only for fundamental frequency to measure damping and natural frequency for characterization of vibration properties. Results showed that 20 % improvement in tensile strength was seen at NS content of 3 wt%, while flexural strength was increased by 35.7% according to unmodified CKFRE samples. It was concluded that interaction of NS particles with epoxy and fiber leading to improve interfacial stress resulted in a significant effect on dynamic properties in terms of natural frequency and damping ratio.

Keywords: Nano-silica; Carbon/Kevlar fiber; Epoxy; Tensile; Flexural; Vibration; Damping.

1. Introduction

The applications of polymer composites have been increased to provide superior properties as incorporating high strength fibers to brittle matrix. Fiber reinforced polymer composites exhibit high specific stiffness, strength and resistance to fatigue loads in addition to ease of fabrication and low cost as compared to conventional engineering materials, like steel and aluminum. Therefore, these composites have generated wide interest in several high technology of engineering fields, especially in automobile, aerospace, sport and infrastructure industry. In addition, fiber reinforced composite laminates are used in several parts of panels for cars and truck cabs, fuselage skin of airplanes, helicopters, fishing rods, tennis rackets, sport shoes, and golf club shafts. Woven hybrid laminates have high resistance to crack growth due to the interlacing architecture of the fiber (weft and warp yarns) bundles, and they also have high strain to failure ratio in tension, compression and impact [1- 3]. In the high performance of composites, epoxy resin has been most commonly used for thermosetting polymer composites due to its high stiffness, dimensional stability and chemical resistance characteristic [4], and fibers of glass, carbon and Kevlar are extensively preferred for major reinforcing materials in fiber reinforced composites [5]. Singh et al. [6] presented a comprehensive study about the applications and characteristics of Kevlar fiber. It was shown that the physical nature of the Kevlar fabric was attributed to its inherent and unique properties such as high specific strength and modulus. Woo and Kim [7] investigated the effects of strain-rate on compressive behavior of the carbon/Kevlar hybrid composite laminates. It was concluded that the failure characteristics of the hybrid carbon/Kevlar samples showed initially matrix cracks, then followed a brittle carbon fiber breakage, and finally high amount of damage mechanisms were occurred such as multiple fiber ruptures, fiber-matrix deboning, fiber pull-out, breakage in the Kevlar fiber tips including splitting, excessive deformation, and delamination. Wan et al. [8] studied hybridization effects on fiber reinforced carbon/Kevlar hybrid composites in attempt to show positive hybrid effect on flexural strength properties. It was stated that fiber/matrix interfacial stress played an important role on flexural properties of the hybrid samples.

Pincheira et al. [9] investigated the effects of Kevlar fiber hybridization on mechanical properties of a twill weave hybrid carbon/Kevlar fiber reinforced epoxy matrix composites for different combinations. It was showed that the incorporation of Kevlar fibers to the hybrid samples resulted in increasing of ductile characteristics of the hybrid sample, leading to increase in toughness property due to Kevlar fibers.

One of the way to achieve increasing in mechanical behavior of composite materials is to combine different types of micro- and nano-fillers within the common polymeric matrix, and these composites are called as nano-based composites exhibiting one or more nano-scale of dimensions [10-20]. Recently, vibration and damping characteristics have gained a significant attraction for polymer composites modified with incorporation of nanoparticles like nano-clay, carbon nanotube (CNT) and nano-silica [21-26]. Gupta et al. [27] conducted vibration tests to determine dynamic characteristics like storage modulus, loss modulus or loss factor of the vinyl ester composites containing nano-clay and flake graphite nano-platelets at 1.25 and 2.5 wt%. The results showed that incorporation of nano-clay particles significantly affected on dynamic properties in terms of storage and loss modulus. Alva and Raja [28] characterized the dynamic properties of hybrid composites reinforced with CNT and Al_2O_3 nanoparticles within the common matrix of epoxy resin. The dynamic modulus with damping properties was measured using from vibration tests, and hybridization with CNT and Al_2O_3 nanoparticles contributed to improve damping and dynamic modulus characteristics of the overall composite samples. Chandradass et al. [29] investigated the vibration behavior of glass fabric/vinyl ester composites with inclusion of nano-clay particles at different weight contents of 0, 1, 3 and 5%. The results showed that incorporation of organically modified nano-clay particles within glass fabric/vinyl ester composites significantly increased natural frequency due to the increasing in elastic modulus, and improvement in damping ratio was reached the highest value at nano-clay weight content of 3%. Huang and Tsai [30] studied on vibration damping properties using Half-power bandwidth method of composite laminates while incorporation of rubber and nano-silica particle into the composite samples, and it was shown that inclusion of rubber and nano-silica particles significantly enhanced damping properties of the samples. Khan et al. [31] conducted vibration tests to study influence of CNT particles on damping properties of carbon fiber reinforced composites, and showed significantly increasing in the damping property in terms of loss modulus of carbon fiber reinforced polymer composites with incorporation of multi-walled CNT particles.

According to the literature survey, it is concluded that the effects of various contents of nano-scale particles on the mechanical properties of composites have been investigated by many researchers. To the best of author's knowledge, no study has been found to report the tensile, flexural, vibration, and damping properties of CKFRE composites with incorporation of silica nanoparticles in the open literature. The objective of this work is to examine the tensile, flexural, and vibration-damping properties of intraply carbon/Kevlar fiber reinforced epoxy composites with incorporation of NS particles at different weight contents (0.5, 1, 1.5, 2.5, and 3 wt%). Failure and fracture surfaces were screened by using scanning electron microscopy (SEM) to analyze effects of NS contents on damage mechanisms of the composite samples.

2. Experimental Procedure

2.1. Materials and production

An epoxy resin (MGS L285) was used as matrix by mixing a hardener (MGS H285) with stoichiometric weight ratio of 100/40. The twill 2/2 woven carbon/Kevlar fabric with areal density of 190 g/m^2 and thickness of 0.24 mm was used as major reinforcing material. All chemical materials and fiber were supplied from DOST Chemical Industrial Raw Materials Industry, Turkey. NS particles was obtained from Grafen Chemical Industries, Turkey. NS particles exhibit thickness of 1-10 nm diameter, lateral width of 0.5-2 µm, and bulk density of 200-500 kg/m^3. Samples were prepared as eight layers with five different nano-silica contents of 0.5, 1, 1.5, 2.5 and 3 wt% as well as pure CKFRE samples. Fiber fabrics were wetted by the application of epoxy resin, and laid layer by layer by using hand layup process. Wetted fabrics were placed on flat mold, and subjected to curing process under temperature of 80°C with pressure of 120 KPa for 1 h curing time. Fig. 1 illustrates the production process for test samples. The manufactured bulk composite samples have 220 mm × 200 mm sizes, and they were cut to the required size for the test measurements according to the ASTM D 638 [32] and ASTM D 790 [33] standards for tensile and flexural tests, respectively. Each of vibration and flexural test specimen has a dimension of 200 mm × 12.7 mm.

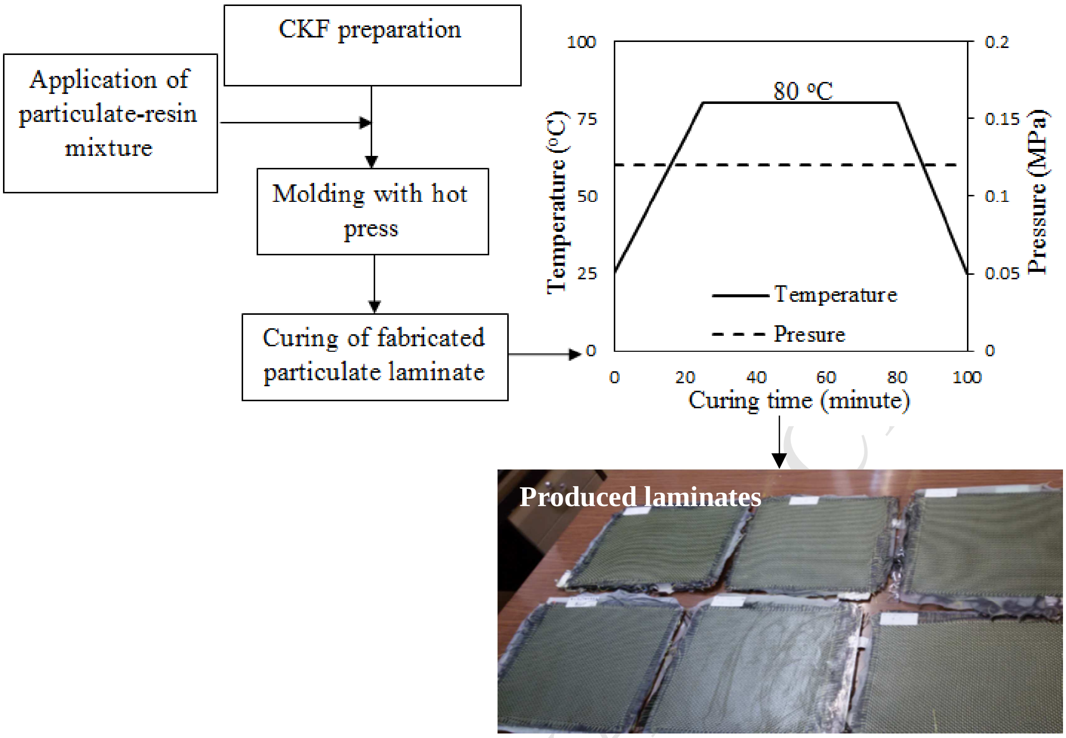


Fig. 1. Flow chart process of laminates fabrication.

2.2. Mechanical Tests

2.2.1. Tensile Tests

Tensile test specimens were prepared according to ASTM D638 standard [32]. Tensile and flexural properties were measured by using Shimadzu AG-X series tensile testing machine having load capacity of 300 kN. Fig. 2 shows the experimental set-up for measuring mechanical properties of the test samples. Five different specimens were tested for tensile test at cross head speed of 2 mm/min up to failure, and their average values were taken into consideration as a final result.

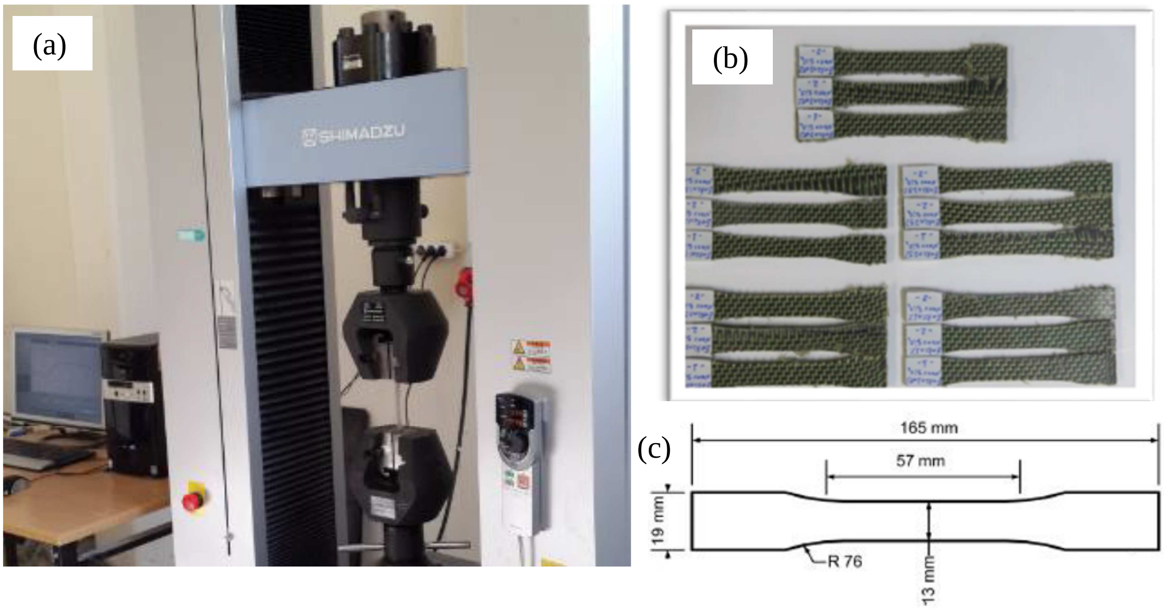


Fig. 2. Tensile test mechanism. (a) Tensile test machine, (b) Samples for tensile tests, (c) Sample dimensions.

2.2.2. Flexural Tests

Flexural properties of the laminated test samples were determined according to the ASTM D790 standard test method [33]. Test samples have a rectangular cross section (L = 200 mm, b = 12.7 mm and h = thickness of the laminate) (Fig. 3). With processing data obtained from test machine, their resulting flexural properties (flexural modulus and strength) were determined by using the equation (1) and (2) [33].

$$\sigma_F = \frac{3P_{\max}L}{2bh^2}\left[1+6\left(\frac{D}{L}\right)^2-4\left(\frac{h}{L}\right)\left(\frac{D}{L}\right)\right] \tag{1}$$

$$\varepsilon_F = \frac{6Dh}{L^2} \tag{2}$$

Where L, b and h are the span, width and thickness of the samples, respectively. D is the maximum deflection, and P is the applied load.

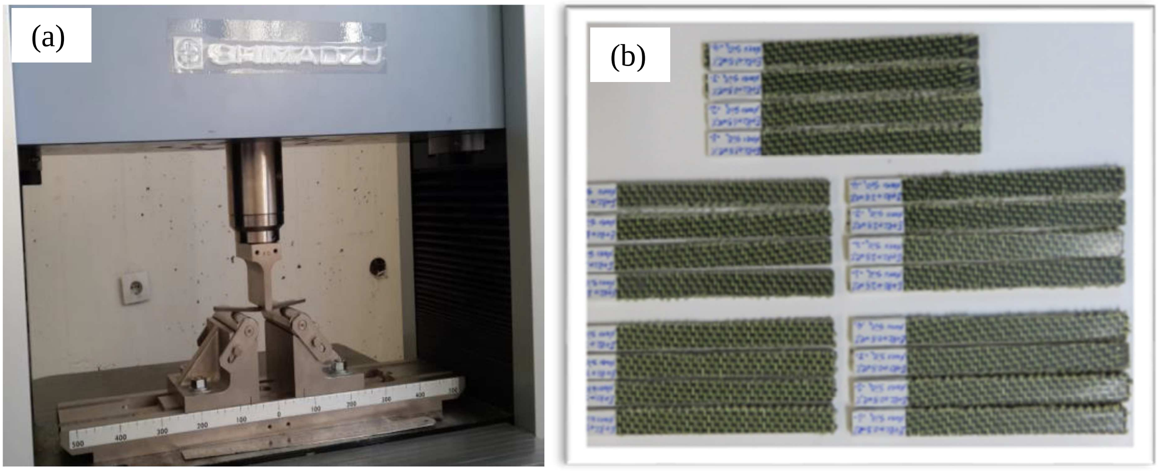


Fig. 3. Flexural test mechanism. (a) Sample in the frame, (b) Test samples.

2.3. Vibration tests

The dynamic characteristics of the samples were measured in accordance with ASTM E756 standard by using an experimental set-up as shown in Fig. 4 [34]. Dynamic properties were determined in terms of natural frequency (ω_n), damping ratio (ξ), storage modulus (E') and loss modulus (E'').During the vibration measurement, a general purpose accelerometer (PCB 352C03 ceramic shear ICP ®), a general purpose modal impact hammer (PCB 086C03), and a data acquisition card (NI 9234) with LABVIEW Signal Express software were used for processing of the output signal and stimulus force signal. Accelerometer was mounted 25 mm distance away from the fixed edge, then sample was stimulated by the application of impact hammer at different excitation points. Frequency response curves were plotted on the screen from output signal with help of NI Signal Express software. Frequency responses were extracted within the constant frequency range from 0 Hz to 500 Hz. Five different points and samples were tested to measure vibration properties, and their average values were taken as consideration.

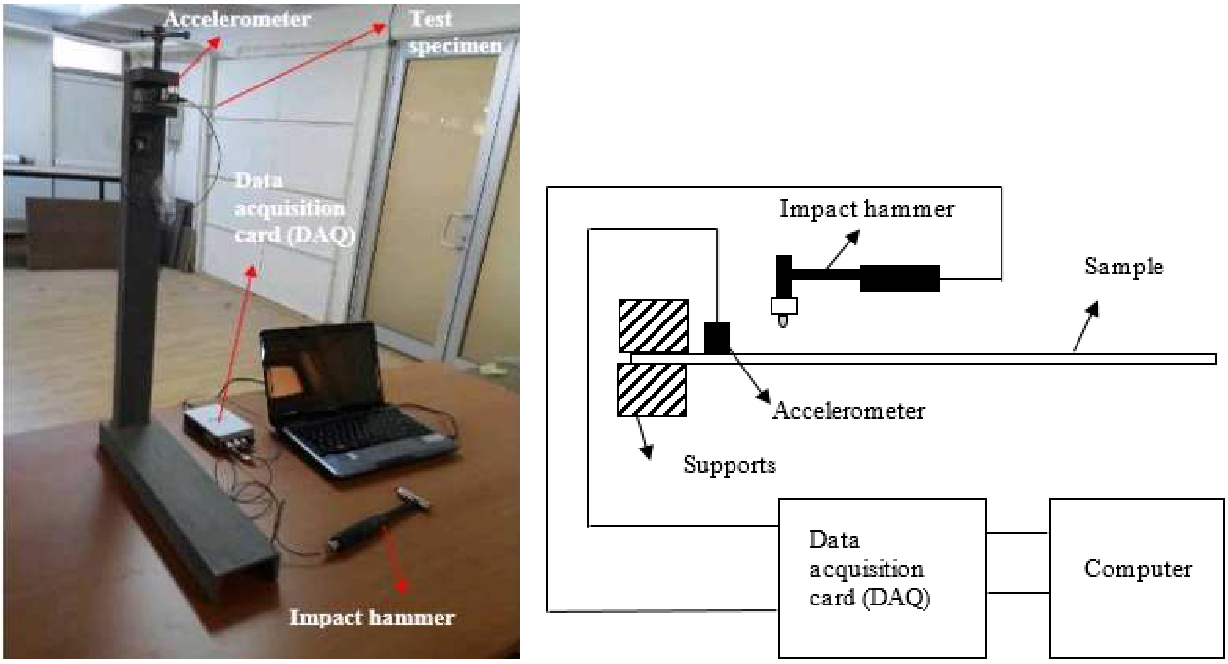


Fig. 4. Vibration test mechanism.

Material storage modulus ($E^{'}$) can be obtained from Euler–Bernoulli beam theory as [35]:

$$\omega_1 = \frac{1.875^2}{2\pi L^2}\sqrt{\frac{E^{'} I}{\rho A}} \qquad (3)$$

Where ω_1 the natural frequency of the first mode, L is the free length of the beam, ρ is the density of the beam, I is the moment of inertia for the given cross-section of beam, and A is the cross-section of the beam. Then, damping ratio was calculated from equation 4 [35].

$$\xi = \frac{\omega_2 - \omega_1}{2\omega_n} \qquad (4)$$

Where ξ is the damping ratio, ω_n is the natural frequency of first mode, and $\omega_2 - \omega_1$ is the bandwidth. Similarly, loss modulus of the beam ($E^{''}$) can be found using storage modulus. Relationship between loss and storage modulus is given in equation 5 [35]:

$$E^{''}(\omega) = 2E^{'}(\omega)\xi(\omega) \qquad (5)$$

3. Result and discussions

3.1. Tensile and flexural test results

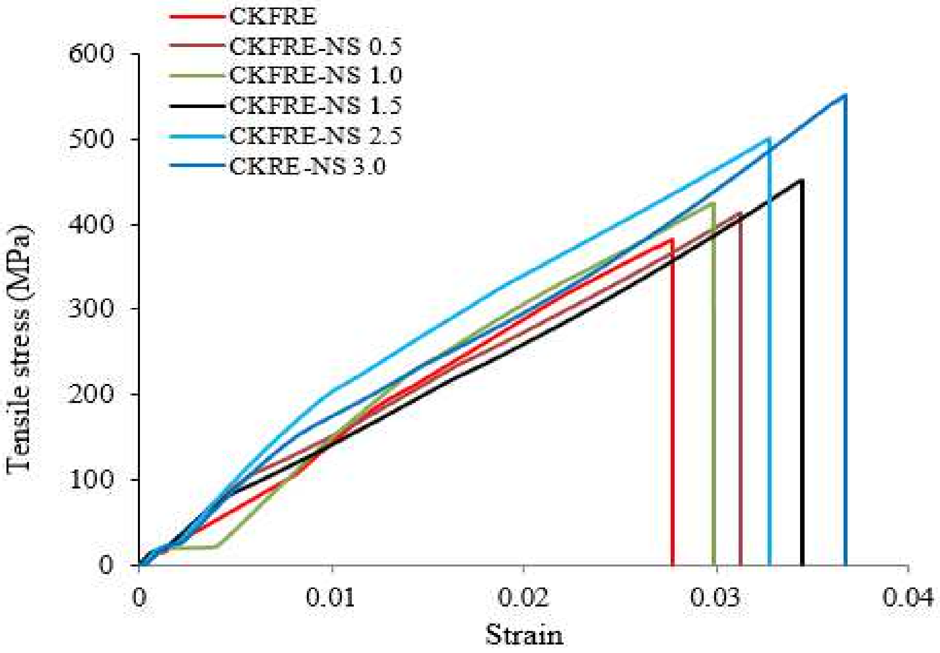
Tensile and flexural tests were presented in Table 1, and their stress-strain curves were displayed in Fig. 5. It is clear from Table 1, tensile strength and modulus was reached the highest value at NS content of 3 and 0.5 wt%, respectively. Tensile strength was increased from 371.74 MPa to 444.98 MPa resulting in 46.8% improvement while modulus showed 31% improvement compared with unmodified CKFRE samples. For flexural properties, maximum enhancement was recorded as 18.1% for flexural strength at NS content of 1.5 wt%, while modulus exhibited the highest value with improvement of 4.1% at NS content of 1.5 wt%.

Table 1
Tensile and flexural test results.

Composite type	NS content (wt%)	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
CKFRE	0	371.74	32.28	442.64	9.74
CKFRE-$NS_{0.5}$	0.5	393.60	42.44	508.62	10.36
CKFRE-NS_1	1	395.21	36.11	547.41	10.12
CKFRE-$NS_{1.5}$	1.5	405.48	30.62	600.86	10.15
CKFRE-$NS_{2.5}$	2.5	427.27	27.74	585.95	8.19
CKFRE-NS_3	3	444.98	25.97	496.79	7.94

Fig. 5 compares the tensile and flexural behavior of samples according to NS inclusion, implying that samples have shown brittle nature as the inclusion of NS in the epoxy resin, and maximum elongation as well as their strength value at breaking point has also been increased. This was suggested that the incorporation of NS particles led to enhance interfacial bonding strength between NS particles-fiber-epoxy interactions, resulting in increasing of the load transfer between nanoparticles and epoxy interaction. Several studies have shown that incorporation of nano-scale particle in the composite systems result in substantially increasing in mechanical properties at a certain amount of particle loading [12, 14, 16]. Therefore, the enhancement of mechanical properties was attributed to the perfect functionalization of NS particles with epoxy and fibers leading to generate increasing in interfacial strength. Flexural and tensile modulus reached the highest value at NS content of 0.5 wt%, and further NS inclusion resulted in a reverse effect resulting in decreasing of flexural and tensile modulus values, and also caused to decrease in load/deformation ratios. This was also attributed to the fact of interfacial strength at the interfacial area of the NS particles and epoxy system those effecting deformability of overall composite structure. Decreasing in mechanical properties with further NS loading after the highest value was explained the fact of agglomeration or aggregation effect leading to decrease in load transfer between particle and matrix.

Three point bending test procedures were performed to measure flexural test in accordance with ASTM D 790 standards. During the flexural tests, layers at back side of the samples were in tension while layers at front side of the samples were in compressive, resulting in tensile and compressive stresses, respectively. In addition, micro buckling failures were observed at the compressive sides of the layers while fiber ruptures due to the tensile stress at the tension sides were dominant failure characteristics as a variation of NS content in the epoxy resin, and difference in mechanical properties of twill weaved carbon and Kevlar fiber fabric resulted in a variation by means of crack propagation at the fracture points. This can be explained the geometry of fiber architecture and mechanical characteristics of the fibers. It is noted here that, the addition of NS particles by 1.5 w% contributed the enhancement of flexural strength until reaching to its highest value (600.86 MPa). However, the flexural strength values were gradually decreased after further NS loading from 1.5 wt%, but still these values greater than unfilled CKFRE composite.



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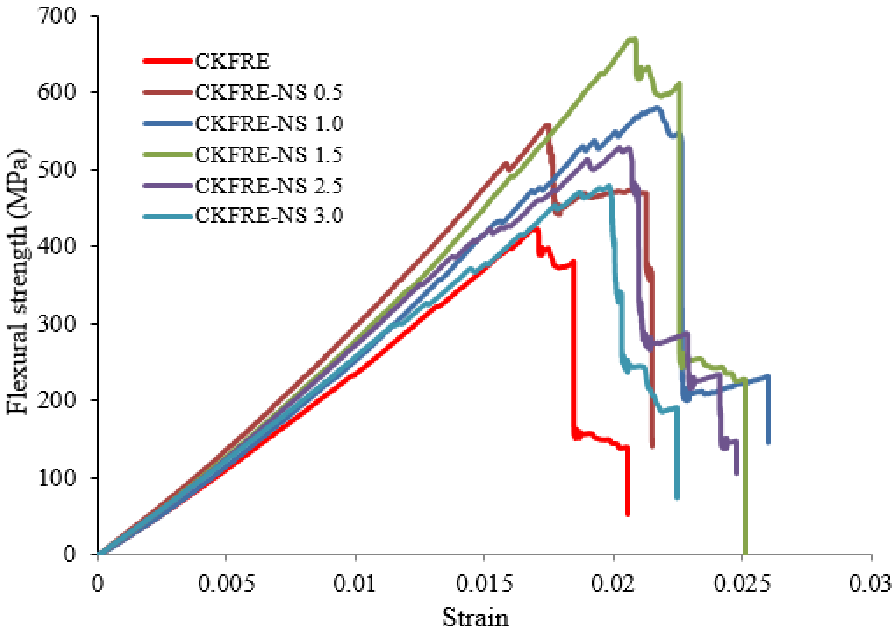


(b)

Fig. 5. Stress-strain behavior of the tested samples. (a) Tensile tests, (b) Flexural tests.

The failure types of tensile and flexural samples are illustrated in Fig. 6, and SEM micrographs around the fractured region for NS particle contents of (0.5, 1, 1.5, 2.5 and 3 wt%) are also shown in Fig. 7. It is clear from Fig. 7 that SEM images showed an uniformly distribution of NS particles within the epoxy system, and this uniform dispersion of NS particles results in efficiently transferring load transfer between particle and matrix, leading to enhance mechanical properties. As a side note, failure characteristics were effected also the content of NS particles, for example high content of NS particle loading resulted in high amount of delamination and fiber breakages due to agglomeration effects leading to decrease in interfacial stress between NS particle and epoxy resin. Tensile test samples showed a brittle nature, rupturing near the clamped edges, and the amount of matrix delamination between carbon and Kevlar fibers were also visible due to the differences in mechanical properties of these fibers under the tensile and flexural loading.

Fig.6. Failure types of composites after the mechanical tests.

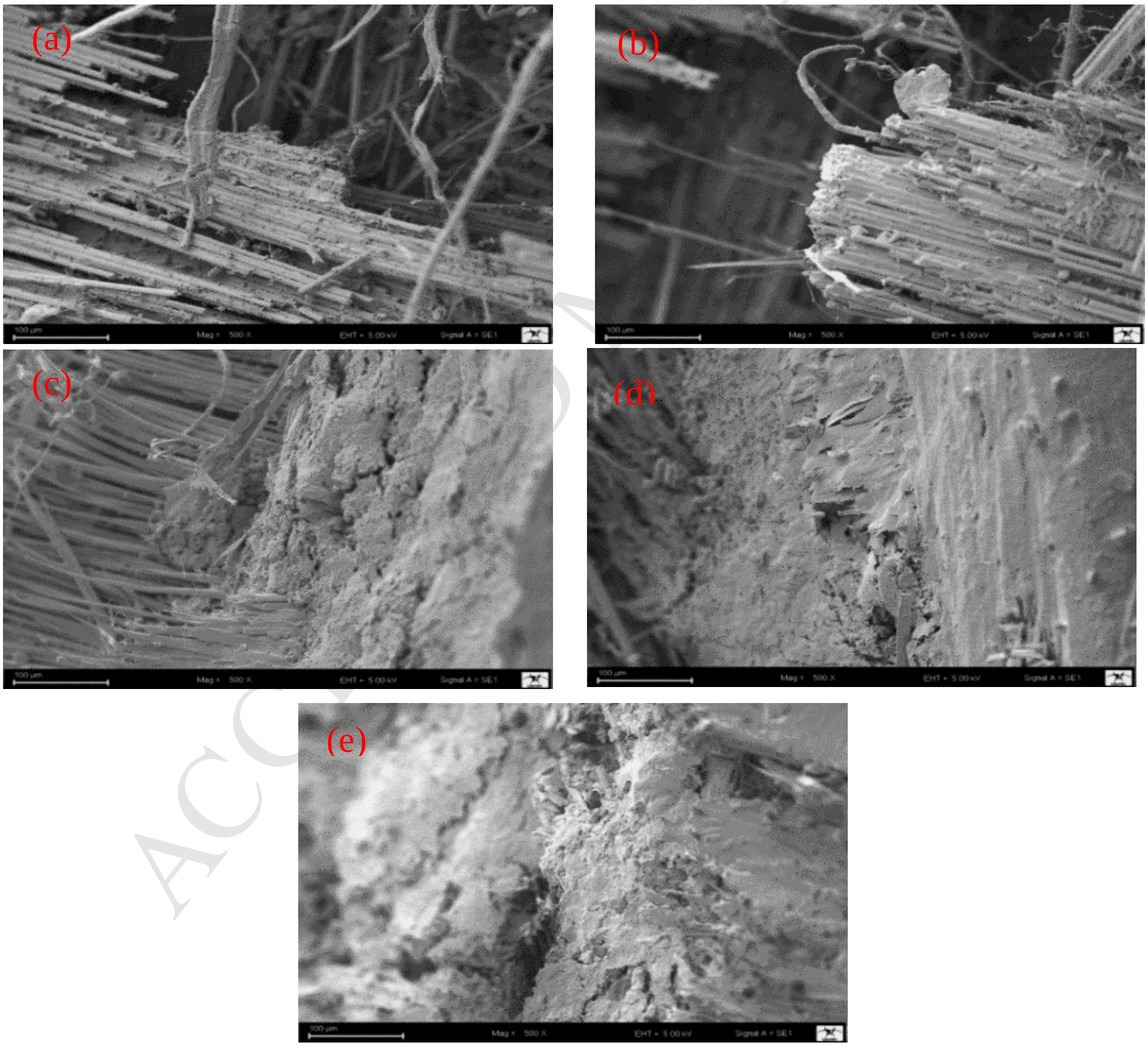


Fig.7. SEM photographs for cracked surfaces of failed specimens at different NS weight contents. (a) 0.5, (b) 1 (c) 1.5, (d) 2.5, (e) 3.

3.2. Vibration test results

Vibration tests were performed by assisting experimental modal analysis only for fundamental frequency, and results were presented in Table 2. For evaluating acceleration vs time responses, different points were excited over the surface of the samples by the application of impact hammer, and most suitable results implying the damping characteristics of the samples were recorded as given in Table 3. It is concluded that natural frequency has been increased by 20.5% from 77.62 Hz to 93.6 Hz when incorporation of NS at 0.5 wt%, and additionally NS loading after the NS content of 0.5 wt% resulted in decreasing of natural frequency. This can be attributed reduction in stiffness due to the agglomeration effect leading to decrease the load transfer between particle and matrix. However, damping is a material property itself, and strictly depends on material microstructure and viscoelastic properties. Inclusion of NS particles contribute the reduction in damping property up to the NS content of 0.5 wt%, then followed increasing trend. This slight reduction in damping ratio can be attributed the increasing of natural frequency and decreasing of slippage effect between NS particles and matrix, while improvement in damping ratio after the NS content of 0.5 wt% was attributed the increasing of slippage effect. In addition, agglomeration is a factor for damping ratio due to reduction in load transfer between particle and matrix, and significantly effecting slippage effect leading to decreasing in absorption of vibration energy efficiently.

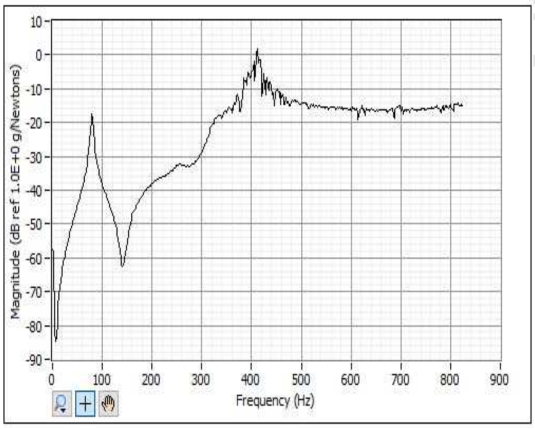
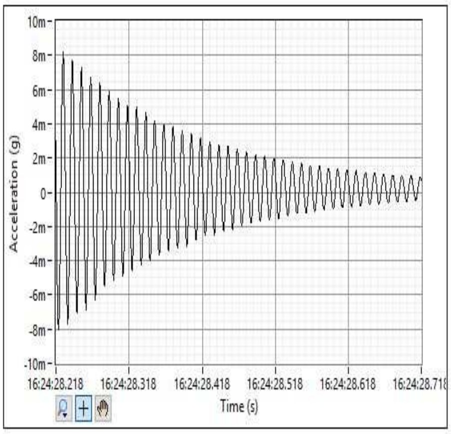
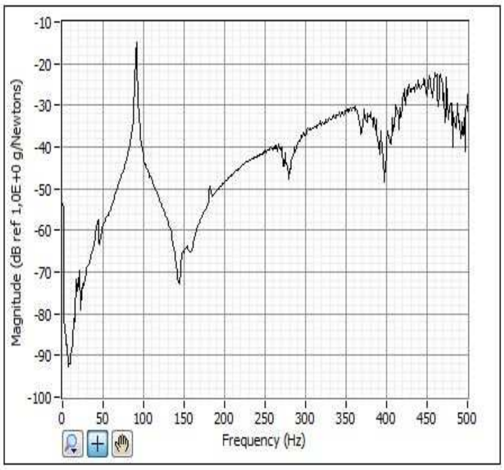
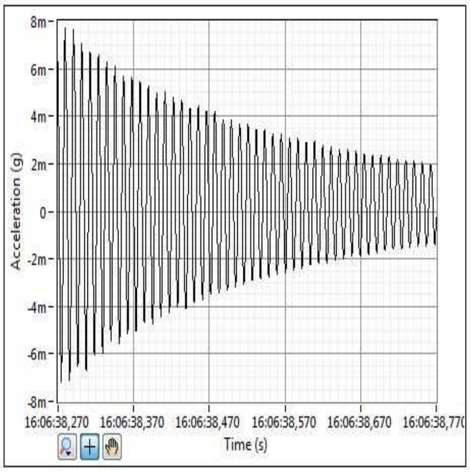
Table 2
Vibration test results.

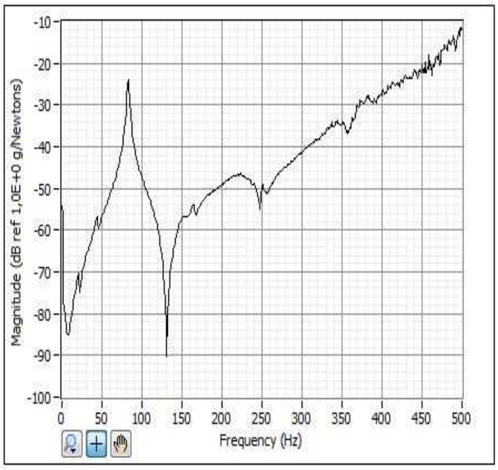
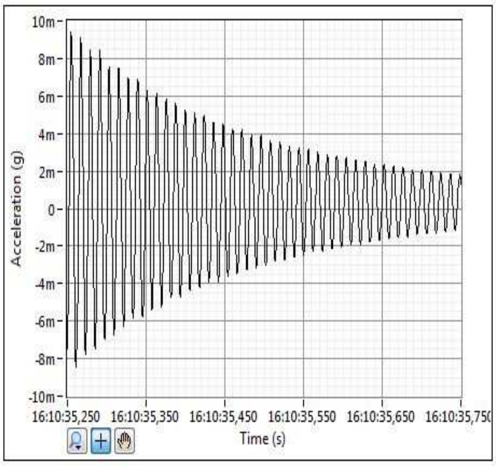
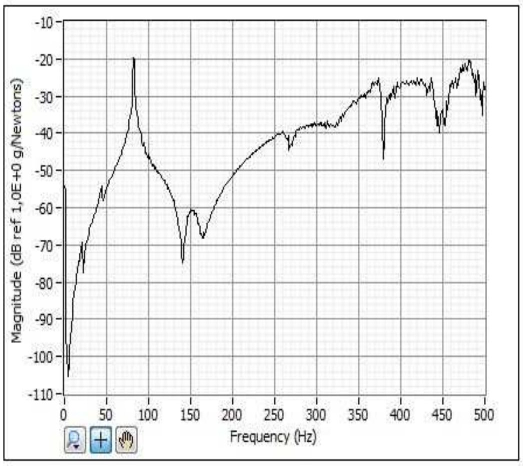
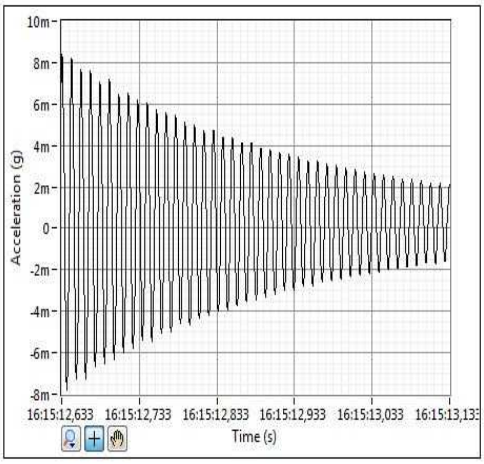
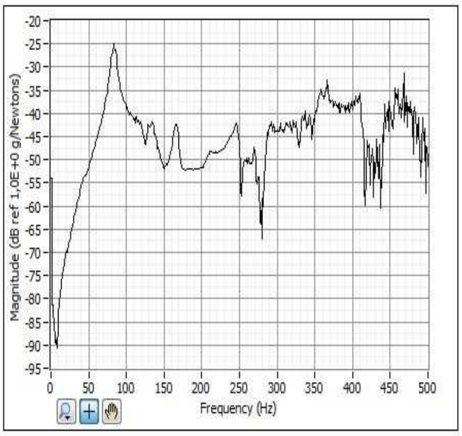
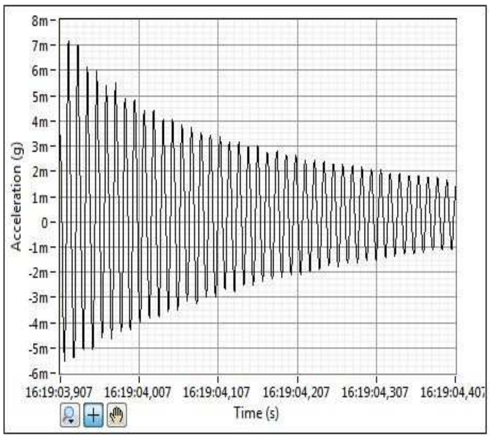
Composite type	NS content (wt%)	Natural frequency, ω_n (Hz)	Damping ratio, ξ
CKFRE	0	77.62	0.262
CKFRE-NS$_{0.5}$	0.5	193.6	0.163
CKFRE-NS$_{1}$	1	84.23	0.166
CKFRE-NS$_{1.5}$	1.5	85.88	0.182
CKFRE-NS$_{2.5}$	2.5	79.67	0.230
CKFRE-NS$_{3}$	3	86.01	0.239

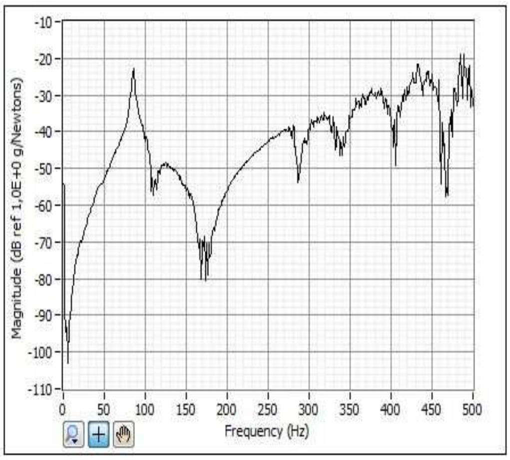
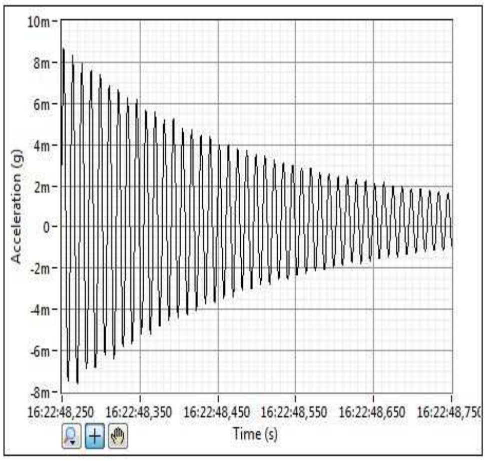
As it is clear from Table 3, the fundamental frequency of the CKFRE samples was clearly observed within the frequency range from 0 to 500 Hz. Acceleration responses were recorded within the constant time interval of 0.5 sec indicating the damping property of the CKFRE samples with and without NS inclusion. It is noted here that increasing of natural frequency resulted in degreasing of damping property leading to enhancement of vibrational energy. In this way, sample was reached the stable condition for a long time. When time responses compared, unmodified CKFRE samples showed the shortest time to reach stable condition indicating high damping capacity as a results highest slippage effect between NS particle and epoxy matrix.

Table 3

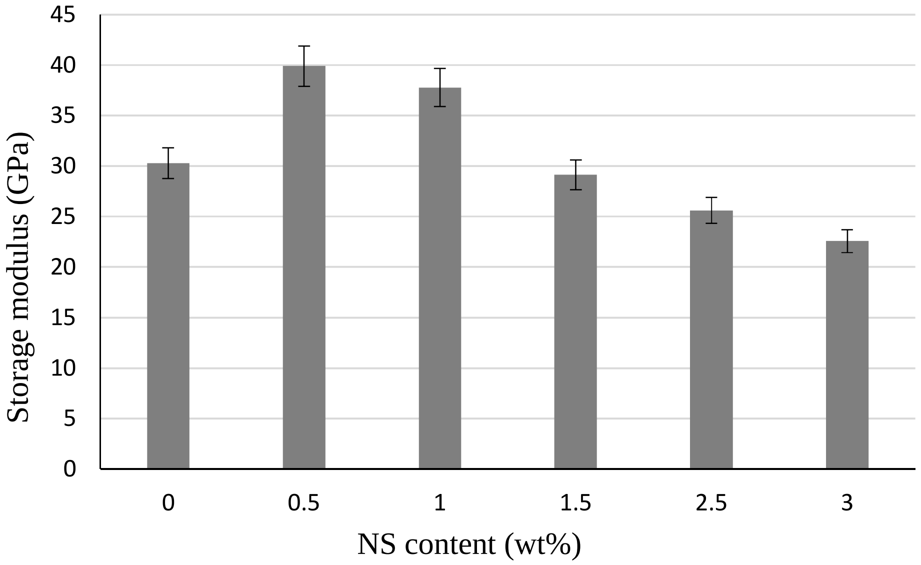
Frequency response and acceleration curves of the samples.

Composite type	Frequency, Hz	Time, s
CKFRE		
CKFRE-$NS_{0.5}$		

CKFRE-NS$_1$		
CKFRE-NS$_{1.5}$		
CKFRE-NS$_{2.5}$		

CKFRE-NS$_3$		

Dynamic mechanical properties of composites were characterized in terms of loss and storage modulus at room temperature of 25 ^{o}C. Loss modulus which is responsible for damping properties of composites was evaluated in order to better understanding of the ability of energy dissipation in the composite laminates, while incorporating of NS particles in CKFRE composite. In this way, variation of loss and storage modulus was explained the fact of interfacial strength between NS-fiber-epoxy interactions playing an important role for dissipation of energy in the composite laminates. Fig. 8 illustrates the comparison of loss and storage modulus values of the test samples according to NS content. It is clear that sample of CKFRE-NS0.5 samples have shown the highest storage modulus while loss modulus was maximum at NS content of 0.5 wt%. Thus, the sample of CKFRE-NS$_{0.5}$ exhibits the highest elastic modulus that is responsible for high natural frequency, showing high dissipation energy per cycle of damping than other composites. A decreasing trend in terms of storage was observed after the NS content of 0.5 wt%, and this was also attributed to the decreasing of interfacial bonding of NS-fiber-epoxy interfaces due to agglomeration effect.



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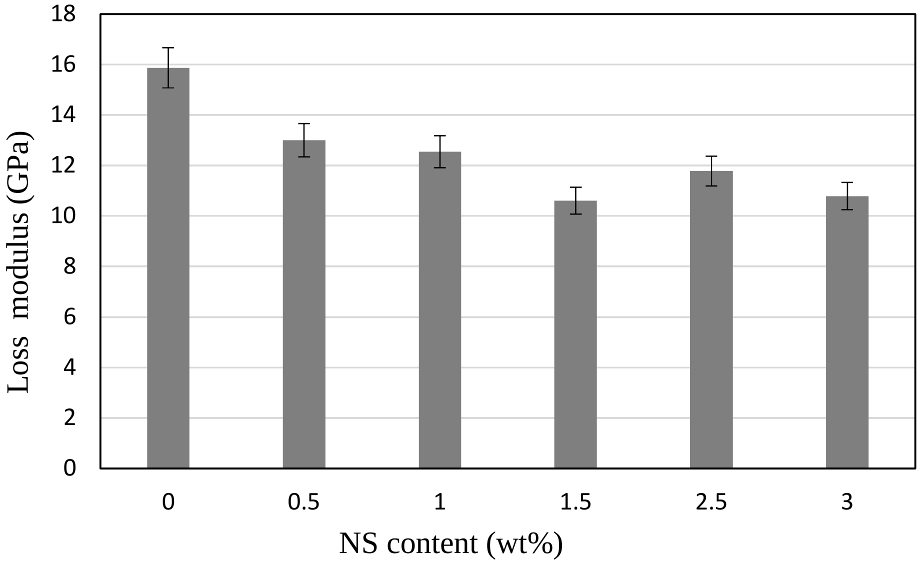

(b)

Fig. 8. Dynamic mechanical properties of the samples. (a) Storage modulus, (b) Loss modulus.

4. Conclusions

In this study, the effects of silica nanoparticles incorporation on mechanical and vibration properties of twill weaved intra-ply carbon/Kevlar hybrid composites were investigated for different weight contents of NS particles. Based on the results of mechanical and vibration tests from this study, following conclusions can be drawn:

- Incorporation of NS particle in the CKFRE composites results in a significant enhancement for tensile and flexural strength, and this was attributed the perfect adhesion of NS particles with epoxy/fiber system leading to increase in load transfer between particle and matrix,
- Further inclusion of NS particles into the epoxy resin after the NS content of 0.5 wt% resulted in decreasing in tensile and flexural modulus of the CKFRE composite,
- The amount of damage mechanisms over the failure surfaces was strictly depends on the content and uniformly dispersion of NS particles in the epoxy resin,
- Incorporation of NS particles in the epoxy resin significantly affected on the natural frequency of CKFRE composites, resulting in maximum improvement of 20.5% at NS content of 0.5 wt%, while damping property decreased by 37% according to unmodified CKFRE samples,
- Decreasing of slippage effect resulted in reduction in damping property as a result of poor interfacial stress between NS particle and matrix,
- Finally, it is possible to design the structures made of CKFRE composites to meet high mechanical and dynamic performance as desired properties with incorporating NS particles in the epoxy resin.

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