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LARGE AMPLITUDE FREE VIBRATIONS OF SPIDER WEB STRUCTURES

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Summary. Most research into spider web structures have considered small deformation theory and small amplitude analysis. In reality, spider web structures, which are slender by nature, are more prone to large-amplitude load effects. This paper firstly presents a numerical study into large amplitude free vibrations of spider web structures. Highly coupled geometry and material nonlinearities have been formulated to establish the finite element models of spider web structures. Validation has been carried out using previous research studies into spider web vibrations. Very good agreement has been obtained for linear and nonlinear results. The validated FEM has been further extended to investigate the large amplitude effect on natural frequencies and corresponding mode shapes of highly-slender spider webs. Interestingly, we are the first to report the dynamic softening and hardening phenomenon in the slender spider web structures.

1 INTRODUCTION

The function of a spider web is to capture and hold a rapidly flying insect, which shows that the spider web has excellent flexibility and resilience. Two aspects of the design of the web make this possible: the optimized spider silk and the design of the web. Spider silk is one of bio-inspired materials that have shown excellent performance exceeding artificial materials in their properties [1]. On a weight to weight basis, its tensile strength is sometimes even stronger than steel and some silks are almost as elastic as rubber. On this ground, silks provide a two to three times toughness of synthetic fibres such as Nylon or Kevlar [1]. Unlike man-made polymers, spider silk can improve strength without compromising fracture toughness [2]. Besides the superior material properties of spider silk, spider web structures themselves can be recognised as a pre-stressed system, it is the so called tensegrity (tensional integrity) structures [3]. This sort of structures shows a unique combine of geometry and mechanic, and as a result of the optimal distribution of structural mass, they are highly efficient structures.

This type of structures shows a unique combine of geometry and mechanic, and as a result of the optimal distribution of structural mass, they are highly efficient structures. It is the nature of spider web structures to absorb quick energy as well as constrain drastic oscillations, which due to prey impact. Moreover, a localized damage is a universal feature of spider webs. When spider web is subjected to local loading, failure is limited to the loading threads and the loaded thread becomes a sacrificial element to keep the majority of the web remains intact, and actually spider webs strength after slightly damaged [4]. In 2012, MIT researchers found that the reason why spider webs are so resilient is not only because the silk's exceptional strength, it is the distinctive combination of strength and stretchiness and the geometrical arrangement in a web [4]. However, many researches focus on the outstanding properties of silk rather than the spider structure itself. Hence, this research will investigate large amplitude free vibration behaviour of the spider web structure and the corresponding mode shapes. This better insight in its engineering performance can unleash its applications in battle and defence technology. The large-deformable finite element 3D model of spider web structures with and without geometric nonlinearities is developed by using Abaqus. According to the virtual work-energy theory, the model is formed from the strain energy owe to axial deformation, kinetic energy owes to the spider web movement and the virtual work due to the self-weight per unit unstretched length, and the concept of large-strain, large-deformation principle has been used to evaluate natural frequencies and corresponding mode shapes with geometric nonlinearity. In this paper, critical review of the relevant published literature shows that large-amplitude vibrations of spider web are critical to impulsive responses and have not been evaluated. Therefore, we are the first to investigate this nonlinear dynamic behavior of the spider web system.

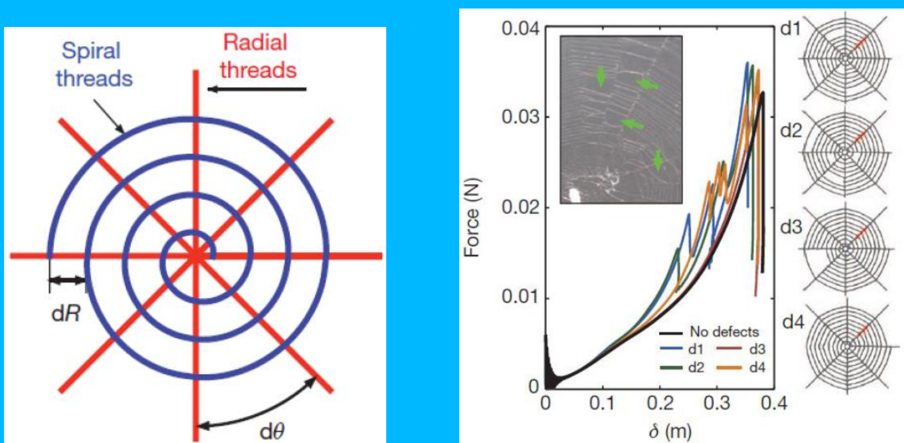
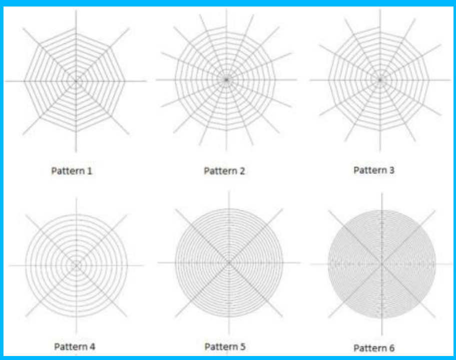


Figure 1: Schematic geometry and behaviour of spider web [4]

2 NATURE OF SPIDER WEBS

The spider web is the device that helps spiders to trap insects for food. Several different sorts of silk such as viscid, dragline, glue-like, minor, wrapping, attachment and cocoon silk can be used in web construction [5]. Several different sorts of spider webs can be found in the wild, including spiral orb webs, tangle webs or cobwebs, funnel webs, tubular webs, sheet webs, dome or tent webs, and orb web is the traditional type spider web which can be seen frequently around. The function of an orb web is to capture and hold a rapidly flying insect, which shows that the orb web has excellent flexibility and resilience [6]. Fig 1 shows the schematic geometry of spider web. The overall size of different orb webs can change from centimetres to meters. In the real word, spider webs actually are highly organized geometry structures.



Material	Density (kg/m^3)	Tensile modulus(GPa)	Poisson's ration	Strength (GPa)	Strain %
Dragline	1098	34	0.49	1.75	26

Figure 2: Patterns of spider web in this study

3 MODELLING

Large-deformable finite element models of spider web structures with geometric nonlinearities have been developed using ABAQUS CAE. The spider web model has been developed on a 2-D plane (X and Y axis) in a 3D space where its free vibrations are often induced out of plane (Z axis). For linear analysis, five different patterns of spider web models have been built to investigate the change of natural frequencies. For geometric nonlinear model, the ratio of natural frequencies extracted from large amplitude free vibration over linear vibration, and corresponding mode shapes have been investigated. The orb web is the traditional type of spider web structures, which can be seen frequently around; therefore, the pattern of the spider web built in this model is an orb web pattern, as shown in Figure 2. A spider web is a cable structure whose segments only sustain tension. Therefore, the boundary condition of spider web structure is the same as that of cable structure, which is pin supports that only permit rotation [7]. A gravity load in axial Z has been applied in the first step of nonlinear analysis. The initial magnitude is $1\times10^{-9}N$ and the increment is $2\times10^{-10}N$. The models have been validated and good agreement is found [8-9].

4 RESULTS AND DISCUSSION

Figure 3 shows the change trend of natural frequencies of spider web under different pretension load. It can be seen, as the pretention load increasing, the natural frequencies increase gently as well. This is because Along with the growth of pretension load, the stiffness of the whole structure is improved, as a result of geometric nonlinearity. And mode shape 8 and 9 have a cross over at the load section between 1.5625×10^{-7} N and 7.8125×10^{-7} N, which cannot be seen clearly due to the natural frequencies of mode 8 and 9 are quite close. This occurrence is attributed to that the hardening phenomenon can influence the performance of spider web structure.

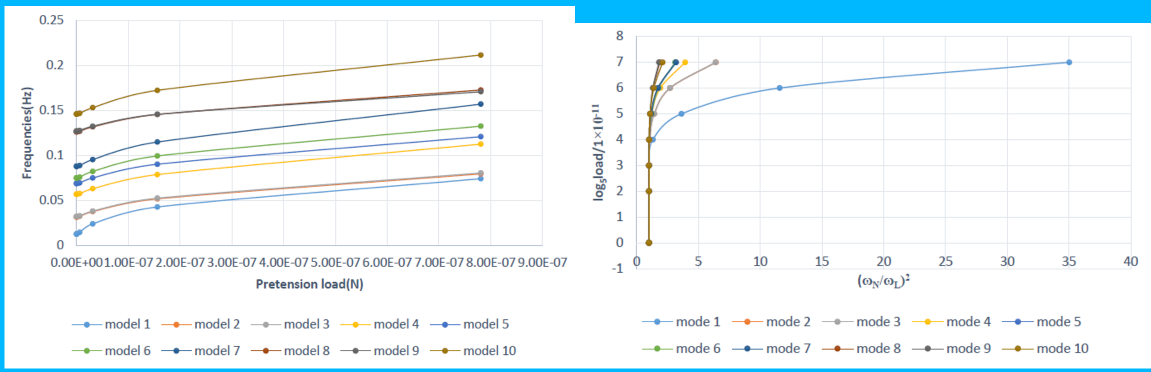


Figure 3: Schematic geometry

Figure 4 is the nonlinear frequency ratios (ωN/ωL)2 of the spider web and it can present that the nonlinear vibrational behavior of the spider web is categorized into hardening type as well. For mode shape 1, the hardening phenomenon is the most obvious one.

5 CONCLUSIONS

Under the FEMs, a pretension load can be applied to create the nonlinear strain-displacement relationship. By increasing the pretension load, the nonlinear vibration behaviour is categorized into hardening type. Natural frequencies increase and the amplitude of free vibration decrease as the result of the hardening.

6 ACKNOWLEDGMENT

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