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Fatigue life assessment of fabric braided composite rubber hose in complicated large deformation cyclic motion

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ABSTRACT

High-pressure braking hose in the automobile power braking system undergoes the complicated large deformation cyclic motion during the driver's steering operation and the up and down motion of vehicle, so that the fatigue damage becomes accumulated in proportional to the cycle number. Since the occurrence of fatigue-induced micro crack in the braking hose may cause the oil leakage, the fatigue life assessment becomes the most important task in the design of high-durable braking hose. In this context, this paper intends to introduce a numerical method for predicting the fatigue life of braking hose in the lamination structure composed of pure rubber and fabric braided layers. A specific trajectory of braking hose in the combined tire's steering and car's up-down motion is defined as the target cyclic path, and the variations in strain and stress fields along the cyclic path are analyzed by the large deformation finite element analysis. The strain and stress cycles in their variations are calculated by the rainflow cycle counting method, and the fatigue life cycle is evaluated by three fatigue life evaluation models, together with the Palmgren–Miner accumulative damage law. The $\varepsilon - N$ curves of rubber layers are obtained by a specially designed displacement-controlled fatigue test using rubber specimens, while the inserted fabric braided layers which are excluded from the fatigue life assessment are modeled as an orthotropic material. The validity of the proposed numerical method is illustrated by the numerical experiments, and the fatigue life cycles to the evaluation model and to the cyclic path are investigated and compared.

1. Introduction

Currently, high-pressure rubber hoses reinforced with various materials are widely used in a variety of engineering applications to convey gas, water and hydraulic oil, and the hydraulic braking hose used in the hydraulic automobile power braking system can be a representative example. The braking hose is generally in three- or five-layered lamination structure composed of pure rubber layers and fabric braided layers, such that pure rubber layers resist oil leakage and chemical damage while the inserted fabric braided layers provide the sufficient structural strength against the large radial expansion of rubber hose [1]. The most important function of the braking hose is to deliver the driver's braking force via working oil without any oil leakage under not only the severe pressure and temperature loadings but also the complicated large deformation cyclic motion. Thus, the fabric braided braking hose should be carefully designed to have the sufficient structural strength and durability against the oil leakage stemming from the excessive expansion, stress relaxation or fatigue-induced micro cracking under the severe thermo-mechanical dynamic loadings [2–4].

The braking hose may, but frequently, lose the desired sealing performance when the micro cracking occurs in operation according to the frequent driver's steering operations and the up and down motions of car. Once this situation is happened, the only way to recover the sealing performance is to replace the damaged braking hose with a new one. The braking hose is to be assembled into an automobile by fixing its ends to the car body and to the strut of tire wheel respectively, so it experiences the complicated large deformation motion by the driver's steering operation and the up and down motion of car. The overall deformed configuration of braking hose varies depending on the strut position, and it is usually characterized by nine distinct strut positions which are resulted from the combination of three steering modes (i.e., left, neutral and right) and three vertical motions of car (i.e., bump, neutral and rebound). Here, the rebound and bump motions denote the up and down motions of car according to the quick start and quick stop or the passing over obstacles [5]. The fatigue damage becomes to be accumulated in proportional to the number of steering operations and the up and down motions because the change in the overall configuration of braking hose is accompanied by the variations in

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both strain and stress fields. The fatigue life evaluation for both car makers and part manufacturing companies has been traditionally performed by defining the trajectories of braking hose between each two positions among the nine strut positions as the target cyclic paths of braking hose. Meanwhile, the braking hose does also experience the stress relaxation and creep during the complicated large deformation motion for long periods of time. However, this complicated viscoelastic behavior is beyond the scope of this study, rather two cyclic motions of braking hose, a left-neutral-right steering cycle at the neutral car position and a bump-neutral-rebound cycle at the neutral steering position, are considered here for the fatigue life assessment of fabric braided braking hose.

The fatigue life of braking hose has been traditionally relied on the experiment at the level of part [6–7], so the highly cost- and time-consuming experiment always becomes a main obstacle in the design of cost-effective high durable braking hose. In this context, it is natural that the replacement of such a painstaking job with the numerical method draws a worldwide attention. The fatigue life estimation methods introduced so far could be classified into two basic approaches, one is the crack nucleation approach and the other is the crack growth approach [8]. In the former approach which traces back to the earliest Wöhler work on railroad axles [9], the fatigue life estimation is formulated in terms of stress, strain or strain energy density at a point within the material under consideration. Since the fatigue life parameters are easily defined in the sense of continuum mechanics, this approach is easy to implement and widely used by engineers. However, restricted to hyperelastic materials like rubber, stress has rarely adopted as a fatigue life parameter [10,11]. It is because not only the fatigue test is usually conducted by controlling the displacement, but the accuracy of stress calculated from strain is not so high owing to the highly nonlinear relation between stress and strain. Meanwhile, the latter approach based on the fracture mechanics predicts the growth of a particular initial crack or flaw which is expected to lead to the final failure. However, in rubber materials, both the up-front information about the state and location of the initial crack causing the final failure and the geometry change of the problem are not available in most cases. For this reason, this approach still remains several problems to be resolved for its robust and unified numerical implementation [8,12–13].

As an extension of out previous work [1] on the fabric braided composite rubber hose composed of five material layers, this paper introduces a numerical method for evaluating the fatigue life of fabric braided braking hose. The variations in strain and stress fields of the braking hose during a cyclic motion are analyzed by the large deformation finite element analysis. The trajectory of the movable end of braking hose, which is to be input as the displacement boundary condition for the nonlinear finite element analysis, is quadratically interpolated using the co-ordinates and rotations of the hose cross-section at the movable end at three discrete positions on the path. Two braided fabric layers inserted between three pure rubber layers are modeled as an orthotropic material, and their equivalent mechanical properties are numerically obtained by our in-house module which was previously developed based on the superposition method and the unit cell finite element analysis [14]. The fatigue life calculation is made only for the inner and outer rubber layers because not only the micro cracking occurs at these two rubber layers but also the braided fabric layers are inserted only to suppress the excessive radial expansion of rubber hose. The hyperelastic behavior of inner and outer rubber layers is modeled by a four-term Mooney–Rivlin material model, and the $\varepsilon - N$ curves of rubber layers are obtained by a specially designed displacement-controlled [8] fatigue test using rubber specimens.

The basic strain-life approach and the Morrow and SWAT (Smith–Watson–Topper) models corrected by the mean strain and stress [15], together with the Palmgren–Miner cumulative damage law [16], are employed to predict the fatigue life. The cycles of signed von Mises strain and stress during a cycle are calculated by the rainflow cycle counting method [17]. An in-house module for evaluating the fatigue life is developed and interfaced with midas NFX [18], a commercial FEM code. The numerical experiment is carried out to support the validity of the proposed numerical method, and the fatigue life cycles computed by three fatigue evaluation models are compared for two cyclic paths.

2. Problem description

2.1. Reinforced rubber hose in complicated large deformation cyclic motion

Fig. 1(a) shows a braking hose used in automobiles to convey high pressure hydraulic oil to the braking disc cylinders. It should satisfy the regularized high pressure-resisting structural strength and the sufficient durability because oil leakage may lead to the fatal car accident. Rubber hose intrinsically possesses high resistance against leakage and chemical reaction, but it may easily reach to the structural failure once the excessively large deformation is repeated during the steering operations and the up and down motions of car. For this reason, the braking hose subject to the pulsating internal oil pressure with the amplitude over 100 MPa is reinforced with fabric braided layers inserted between pure rubber layers as represented in Fig. 1(b). As a sort of laminated composite, the fabric braided layers provide the mechanical strength against the pulsating pressure load while rubber layers resist the leakage and chemical reaction and protect the fabric braided layers from being torn and worn owing to the contact with other adjacent mechanical parts.

The overall deformed configuration of braking hose is definitely dependent of the position and orientation of the strut where the movable end of braking hose is attached, as represented in Fig. 2(a). Both the position and orientation of strut are in turn determined by the steering mode of vehicle and the up and down motion of vehicle. The neutral position corresponds to the straight maneuvering mode without the up and down motion, from which the movable end of braking hose could reach to other possible critical positions depending on the steering mode and the vertical motion of car [5,6]. Both the bump and rebound positions are two possible furthermost up and

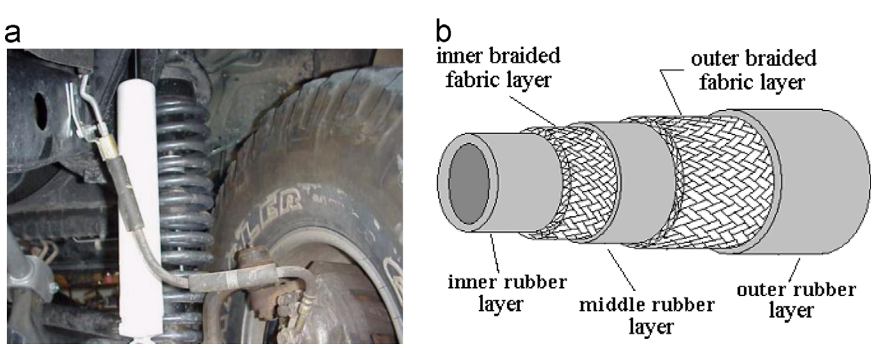

Fig. 1. High pressure braking hose: (a) assembled configuration, (b) layer-wise material composition.