Composite Structures 201 (2018) 1–12

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Investigation of mechanical behavior of weld seams of composite envelopes in airship structures

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ARTICLE INFO

Keywords:
Airship structure
Composite envelope
Weld seam
Noncontact measurement
Elastic constants
Failure mode

ABSTRACT

With the favorable space retaining advantage, airship structures provide a cost-effective approach for the high altitude payload platform. While composite envelopes, the key material for an airship capsule, were extensively studied, the mechanical behavior of weld seams remained unclear. As weld seams may be the authentic controlling factor for the mechanical performance of airship structures, a comprehensive study on its mechanical behavior is necessary. An in-depth investigation revealing the tensile properties of weld seam was carried out in this study. Three types of weld seam specimens were designed and manufactured. To illustrate the microstructure of the weld seams, an electron scanning microscope apparatus was employed conducting observation. Systematic tensile tests were performed on envelopes, weld tapes and weld seams. It was found that the failure occurred at the heated zone rim. Furthermore, noncontact measurement was utilized obtaining the global strain field, based on which elastic constants were calculated. Eventually, a numerical model was proposed to simulate the tensile behavior of the weld seam.

1. Introduction

Different from the airplane, spaceship and man-made satellite, the lift of an airship comes from the inherent buoyancy instead of fuel consumptions. Since airships are able to keep stationary in the altitude up to 30 km, a cost-effective approach for land observation, communication and meteorological data collection becomes available [1]. Generally, airship structures can be divided into three categories, rigid airships with full internal load-bearing truss, semi-rigid airships which commonly possessed a bottom supportive keel and non-rigid airships with few rigid structural components [2]. When the service altitude of an airship is designed higher than 20 km where the atmosphere density is approximately one fourteenth of that on the ground [3], the feasibility of the craft becomes extremely sensitive to the structural form. On this occasion, the non-rigid airship became more applicable than other forms because of its lighter self-weight and favorable flexibility.

A major focus in this field is the fine structural analysis [4–8]. Previous research work mainly discussed the mechanical behavior of the airship hull while various modeling methods were established. Other than rigid and semi-rigid airship form, non-rigid airships possessed few rigid structural components. For this reason, the aerodynamic shape of the airship capsule is maintained by the pressure of the filling gas and the stiffness of stressed composite envelopes. Fig. 1 shows a typical capsule configuration of the non-rigid airship structure. As can be observed from the figure, an airship capsule is usually comprised by identical envelope gores welding together. Only with durable welding seam manufacture, the airship capsule formed a closed air sac.

Since the non-rigid airship is a flexible system, the composite envelope and the weld seam become vital for the whole structure [9]. To conduct structural analyses of airship structures such as deformation calculation, reliability evaluation and failure prediction, an in-depth comprehension of mechanical behavior is necessary for both envelopes and weld seams.

Numerous experiments and analyses were performed to study the composite envelope for airships. Miller and Mandle [10] gave a detailed review of the development and the test methods for the semi-rigid and non-rigid airship envelopes. Maekawa et al. [11] studied various approaches to determine the tear strength of airship envelopes. A 4-meter-long pressurized cylinder test which was close to the authentic airship service condition was conducted. Meng et al. [12] investigated both the uniaxial and the biaxial stress-strain relationship of a specific envelope material. According to their research, the off-axis angle plays an important role in the failure pattern.

However, few researchers addressed the unique mechanical

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https://doi.org/10.1016/j.compstruct.2018.06.019
Received 8 December 2017; Received in revised form 14 May 2018; Accepted 4 June 2018
Available online 05 June 2018

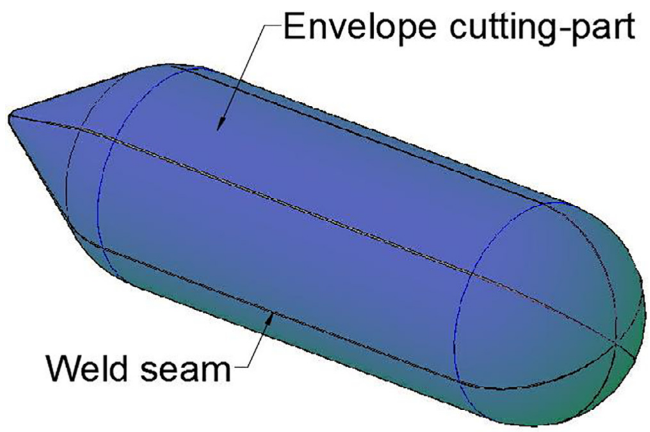

Fig. 1. Schematic diagram of a non-rigid airship capsule.

performance of weld seams, which may be the authentic controlling factor for the mechanical performance of airship structures. Since previous structural analyses usually assumed that airship structures were ideal continuous capsules, the mechanical behavior of weld seams was neglected leading to invalid results of structural analysis. Specifically, fine structural analysis was required for large-scale stratospheric airships considering strict weight control, high strength-to-weight ratio materials and its extreme operation conditions. As current and previous specifications [13,14] concerning airship construction and weld bonding only give rough request on the ultimate strength of weld seams (usually between 0.8 and 1.0 of the uniaxial tensile strength), the mechanical behavior and its influence on the global airship structure remains unclear. To illustrate the loading behavior, the mechanical model and the failure mechanism of weld seam, the investigation on its microstructure, geometrical configuration and welding process influence were necessary. Based on experimentation and analysis, an accurate mechanical model of the weld seam could be built, laying the foundation for structural analyses.

Three types of weld seam were designed and prepared in this study. An electron scanning microscope (SEM) apparatus was employed to observe the microstructure of specimens. Meanwhile, systematic tensile tests were performed. The stress-strain relationship was reported and elastic constants were calculated. Based on test results, the failure modes of weld seams were presented and analyzed. Furthermore, noncontact measurement utilizing digital image correlation technology was fulfilled which would precisely illustrate the global strain field of the area of interest (AOI). Eventually, a numerical model was proposed to simulate the mechanical behavior of the weld seam. Future research work may apply the behavior of weld seams to the global structural strength analysis of an airship structure.

2. Methodology

2.1. Materials

The service conditions of the airship composite envelopes include cyclic temperature loading, high-intensity cosmic rays, ozone oxidation, frequent aerodynamic loading and other extreme factors. Therefore, this material usually comprises of high molecular fabrics laminated with functional treatment. Fig. 2 gives the schematic configuration of an airship composite envelope. In practical airship engineering, the seams are butt-welded strengthening by weld tapes. Consistent with the manufacture process, typical envelope and weld tape materials employed in authentic projects were selected in this study. The basic physical specification for these materials are listed in Table 1. Typical airship envelope materials possess two principal axes, warp and weft, which are usually perpendicular to each other. Due to the manufacture process, the mechanical behavior of two directions diverge distinctively resulting in an orthotropic material [15]. The warp direction with a higher tensile strength is normally used in the structural longitudinal direction. The structural layer was fabricated by Vectran® fibers while the functional layers comprised of gas retention layer, ultraviolet layer, wearable layer, adhesive layer and welding layer.

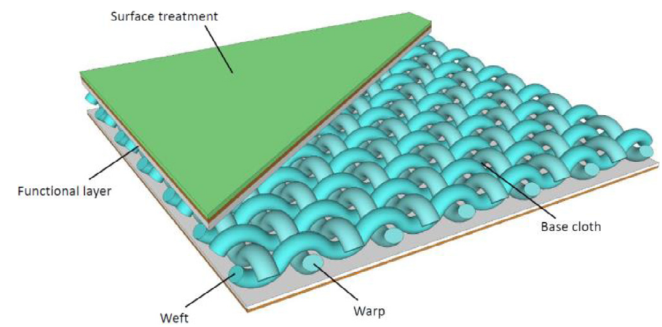

Fig. 2. Schematic configuration of the airship envelope [16].

Table 1
Basic specification for envelope and weld tape materials.

Variable	Envelope	Weld tape
Thickness	0.48 mm	0.44 mm
Areal density	260 g/m^2	275 g/m^2
Weave count	44 × 40 ends/5 cm	38 × 38 ends/5 cm

2.2. Welding seam specimens preparation

The welding seam in authentic airship structures usually adopts butt-welding pattern. For the butt-welding pattern, the two sides of the discontinuous envelope aligned at the interface without overlap. Subsequently, weld tapes were welded onto the surface of both sides providing stiffness and strength. Sometimes, more than one layer of weld tapes were employed in the welding process which may further strengthen the seams and guarantee the helium retaining. High frequency weld and heat weld are two major existing methods to conduct the manufacture. Considering the thermal mechanical properties of the top layer of the envelope, the heat weld is applicable and was therefore chosen in this study.

For the purpose of revealing mechanical similarities and differences, three types of weld seams were designed and produced. Fig. 3 demonstrates the geometrical layout for each kind of specimen.

Inspection of Fig. 1 indicates that the weld seams lie along the longitudinal direction of the airship capsule. Based on this feature, the long side of the tensile specimen should stay in the structural ring direction, which equals the weft direction of the envelope material. The particular specimen preparation process is reported as follows.

- Preliminary material selection. To start with, the sampled material was selected from coiled industrial product. All envelope material sampled in this study was at least 200 mm away from the raw product edge to avoid uneven fabric weaving. Specifically, bow effect, the partial transverse deviation of yarn form leading to non-perpendicular relationship between warp and weft yarns, was strictly controlled. Since bow effect would cause stress concentration and significantly reduce the load bearing capacity, the maximal transverse deviation of yarn form was determined less than 0.5%.
- Cutting piece preparation and surface cleaning. With favorable raw material acquired, an electorally controlled cutting machine was employed to produce different rectangular cutting pieces. For composite envelopes, the geometrical dimension was determined 300 mm × 50 mm while the longer side kept in line with the weft