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# Residual stresses in aerospace structures reinforced with bonded crack retarders

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## Abstract

Bonded crack retarder (BCR) technology is an innovative concept to improve the fatigue performance of aircraft structures. Stiffening “straps” are adhesively bonded to areas where potential fatigue cracking may occur. The straps retard the growth of fatigue cracks, by a combination of the local stiffening effect that reduces the crack driving force, and bridging in the wake of the crack. However, bonded crack retarder results in thermal residual stresses that may adversely affect the performance of the reinforced structure due to extensive fatigue loads in service. This is the first study where we have looked at the application GLARE6/5 fibre metal laminate as a bonded crack retarder onto a structural butt joint and simulated manhole mock-up assemblies containing cold-worked holes. Neutron diffraction was used for residual stress measurements. Results indicate that the strap bonding process has no discernible effect on the magnitude of the compressive cold-working stresses. The use of bonded crack retarders should not, therefore, impair the benefits of cold working of fastener joints in aircraft structures.

**Key words**

Bonded crack retarders, Cold expansion, Fastener holes, GLARE, Residual stress

## Introduction

Structural integrity and fatigue durability are the two most important criteria in aircraft structural design. Mechanically-fastened joints are common design features in aircraft structures as they are economical and easy to maintain. Aircraft structures, therefore often rely on numerous riveted and bolted joints. These joints not only provide load transfer, but also provide a permanent damage resistance bond [1]. Fastener joints are considered as stress raisers and potential failure locations in metallic aerospace structures because the fastener holes act as stress concentrators. Aircraft in service experience cyclic loading which eventually leads to the accumulation of fatigue cracks. Fatigue cracks typically initiate at the flaws and sites of high stress, such as fastener holes, propagating along paths of least resistance, and may individually or cumulatively affect structural performance.

Structural joints based on fasteners result in an increase in weight, and monitoring of fatigue damage requires frequent maintenance of the aircraft which increases the operating cost and influences the economy of the aerospace industry. However, the demands on the use of aircraft have significantly increased in recent years. Owing to this increase in demand, civil aircraft are often operating well beyond their original design service goals, sometimes with different fatigue missions than originally envisaged. The need to ensure continued flight safety has therefore demanded an increased focus on fatigue durability and fail-safety of critical aircraft structures.

In recent years much attention has been paid to reducing fatigue-critical locations and to the use of large one-piece integral structures in aircraft. Such structures significantly reduce the weight and improve the fatigue performance by minimising the number of fasteners used. A potential disadvantage with integral structures is the lack of physical barriers, as currently exist in structures joined with fasteners, that can arrest a growing crack. One promising solution for this is to incorporate crack retarding features into integral structures. The use of fibre-metal laminates as adhesively bonded crack retarders in structural critical locations is of great interest [2-4]. GLARE fibre metal laminates have been used as stiffening straps to improve the fatigue performance/extend the life of critical aircraft structures [5-6]. GLARE is made of thin aluminium sheets, and glass fibres impregnated with epoxy stacked in layers to form a fibre metal laminate. The high damage tolerance of GLARE is derived from the aluminium, combined with high strength derived from the strength of the glass fibres. In the wake of a crack, the of GLARE provides a crack bridging effect. However, if a crack propagates through the strap/ substrate interface, the fatigue crack resistance is governed by the constrained delamination between the strap and the substrate interface.

The principal problem associated with bonded crack retarders is thermal residual stresses which will develop during the strap bonding on to the substrate and significantly affected by the service temperature of the structure. This is because of the difference in coefficient of thermal expansion between the GLARE and the aluminium substrate [7-9 ]. In the aerospace industry, high temperature cure adhesives are preferred to ensure thermal stability of the joint when in-service: aircraft structures can experience on-ground temperatures up to +70˚C. The residual stresses may add to the stress concentration effect at a fastener hole, for example,  and result in fatigue crack initiation.

Owing to the fastener row and the eccentric load path, butt joints in aircraft are highly susceptible to fatigue crack initiation. Under nominal tensile loading, the eccentric load path results in secondary bending of the structure. The maximum moments owing to secondary bending are induced at the fastener rows. The damage tolerance of the butt joint can be improved by the application of a reinforcement strap. The reinforcement strap will have an overall effect of increasing the stiffness of the joint, and thereby, a reduction in secondary bending should be possible [10, 11].

The openings in aircraft skins are usually referred to as manholes. Manholes provide access to aircraft wings, fuel tanks and stabilizers. Generally, a hole or opening in an aircraft structure requires reinforcement to ensure its service life. For bonded crack retarders the reinforced structure requires an additional means of fixing as well as the adhesive layer to increase the structural fail-safety in the event of complete disbond, most likely using riveting or bolting. Current practice is to cold work fastener holes to develop compressive residual stresses through the cold expansion process to enhance the fatigue performance. These stresses will vary through the thickness of the holed plate being higher at the tool exit face compared to the tool entry face. The induced compressive stresses enhance the fatigue resistance of the fastener hole [12-14]. For the multilayer system used in this research, cold expansion was performed after strap bonding onto the metal substrate.

In a previous study [15], we investigated the effect of a GLARE bonded crack retarder on the cold expansion and bolted stresses on coupon specimens with and without a strap and concluded that the magnitude of the compressive stresses at the bore of the hole was not affected by thermal residual stresses. In the current research, we have extended this study to an assembled mock-up with additional interference and load transfer effects. Owing to the complex geometry and the additional load transfer effects, induced thermal residual stresses may significantly affect the cold expansion stresses. Critical aerospace structures require reliable measurements to satisfy the structural integrity and damage tolerance approach. Hence, a thorough understanding of the stresses associated with the holes is essential for accurate estimation of the fatigue life of the reinforced structure. Therefore, the work reported in this paper investigates thermal residual stresses owing to GLARE bonding onto butt joint and manhole structural coupon specimens and their effect on the cold expansion stresses.

## Experimental materials and procedures

### *Materials*

A single-strap-reinforced butt joint and a manhole coupon specimen were manufactured using aluminium alloy 2624-T351. The single-strap reinforced butt joint specimen consists of skin, stringer, and butt strap.  Fig 1 shows the geometrical details of the specimens used in this investigation. GLARE 2 (6/5) was used as the strap, which consists of six aluminium 2024-T351 (0.4 mm thick) alloy sheets and five double layers (0.26 mm thick) of unidirectional glass-fibre-reinforced epoxy stacked in a layered manner. The glass fibres are oriented along the longitudanl direction (perpendicualr to crack growth) of the strap/substrate. For butt strap joint (Fig 1), a GLARE strap is bonded onto the skin plate of 9.6 mm thick. The mechanical properties for substrate, GLARE 2 (6/5) and FM94 are presented in table 1. FM94® supplied by Cytec Ltd  was used to bond the GLARE strap onto the one side of the butt joint skin plate. The curing temperature of the adhesive was 120°C. Prior to adhesive curing, the substrate and the bond surface of the GLARE strap were cleaned thoroughly using alcohol. FM94 adhesive was cut into the desired shape and both FM94 and the GLARE strap were placed onto the substrate. The whole assembly was  then de-bulked via vacuum to ensure that the air has been removed. Finally, the whole assembly is placed in an autoclave for high temperature curing as follows

- Apply vacuum at ambient temperature for a minimum of 15 minutes and increase the temperature at a rate of 3°C/min from ambient to 125 ± 5°C, and increase pressure in autoclave to 520 kPa.
- Vent vacuum when the pressure reached 415 kPa, or when the temperature reached 60°C, then apply a pressure of 520 kPa at 125°C± 5°C for 90 minutes.
- After 90 minutes, turn off the heat and allow to cool to below 60°C, whilst maintaining the pressure, prior to removing the samples from the autoclave

The manhole specimen was machined from Al 2624-T351 using computer numeric control machining. The thickness of the substrate was 6 mm. The manhole specimen was reinforced on both sides, one side with a GLARE 2 (6/5) strap and an Al 2624-T351 metallic strap was placed on the other side as shown in Fig 2. Both the specimens were assembled with interference fit bolts. Prior to assembly the fastener holes were 3% cold expanded using FTI’s split-sleeve technology. The cold expansion mandrel was pulled from the non-reinforced side (inlet) to the reinforced side (outlet).

*Experimental procedures*

Neutron diffraction was used to measure the residual stresses in butt strap and manhole specimens. Residual stress measurements on the single strap butt joint were performed at the ENGIN-X time-of-flight diffractometer at the UK’s ISIS pulsed neutron source [16]; and residual stress measurements on the manhole specimen were performed at the SALSA instrument at the ILL, France [17]. ENGIN-X consists of two detectors placed at ± 90° to the incident beam which allows measurement of strain in two directions simultaneously. The diffracted beam from the specimen contains multiple reflections which are then collected by the detectors. The data collected was analysed by ENGIN-X Script Based Analysis (EX-SBA) software which uses Pawley or Rietveld refinement to determine the lattice spacing ($a$) in the measured direction, which can be used to determine strain and hence stress if sufficient strain components are acquired.

$$\varepsilon(x,y,z) = \frac{a(x,y,z) - a_0}{a_0} \qquad \text{Equation (1)}$$

Where $\varepsilon_{(x,y,z)}$ is the strain in the respective direction, $a_{(x,y,z)}$ is the measured lattice spacing and a0 is the stress-free reference lattice parameter. The stress can be computed by using the three-dimensional form of Hooke’s law.

SALSA is a monochromatic diffractometer uses a monochromatic incident beam to obtain single lattice reflections (311 lattice plane for aluminium) in each direction. The wavelength of the incident neutron beam was 1.648 Å. For both the specimens a gauge volume of 2 × 2 × 2 $\text{mm}^3$ was used. Stress-free reference measurements were performed in all three assumed principal directions (hoop, radial and axial) to account for any texture and plastic anisotropy in the material. Stress-free measurements were performed at a point close to the edge of the specimen well outside the strap bonding region at similar thickness locations (at z = 0.27t and 0.625t from the reinforced side for single strap butt joint and at z = 0.25t for manhole specimen) as the residual stress measurements . This stress-free reference will be used in computation of residual stresses.

## Results and discussion

### *Single strap butt joint specimen*

Single-sided strap bonding introduces thermal residual stresses in the skin plate which may vary through the thickness, being higher at the reinforcing side. Neutron diffraction measurements were performed along the expected crack growth direction (y-direction) from the edge of the bolted hole towards the far end of the specimen as shown in Fig 1.

Measurements were performed in the skin plate at two different thickness locations, i.e. at z = 0.27t and 0.625t from the reinforced side. The results are shown in Fig 3.

From Fig 3 it can be seen that in the hoop direction near the edge of the bolt the stresses are compressive, and vary through the thickness, being higher near the reinforced side. The variation in the hoop stresses through the thickness corresponds to the entry and exit face for the cold expansion mandrel. For the single-strap butt joint specimen, the face away from the reinforcing strap was the outlet face and the reinforced side was the inlet face. Compressive residual stresses will be higher on the outlet face compared to the inlet face owing to higher deformation resulting as the mandrel pushes material from the inlet face towards the outlet face. Measurements remote from the bolted holes showed very low stresses that were reasonably constant.

In Fig 3a and 3b, measurements performed near the edge of the bolts in the radial direction show compressive stresses. As measurements progressed in the y-direction tensile stresses can be observed which are dominant in this direction. This is as expected from the cold expansion process, and the stresses in this direction do not have a detrimental effect on crack growth. Measurements performed away from the bolted hole in the radial direction at z = 0.27t showed tensile stresses that are slightly higher than the stresses at z = 0.625t, though the magnitude of the measured stresses is very low and approach the measurement technique sensitivity. Also, the hydrogen-containing adhesive present in the assembly causes incoherent scattering of the neutrons which impairs the signal-to-noise ratio.

*Manhole specimen*

Residual stress measurements on the manhole specimen were carried out in the substrate (Al 2624-T351) at z = 0.25t at two locations, *i.e.* line 1 and line 2 as shown in Fig 1. The results are shown in Fig 4. In line 1, measurements were performed starting from the edge of the GLARE strap and progressed towards the far end of the specimen as shown in Fig 1b. From Fig 4a, it can be seen that radial compressive stresses were present up to 0.03W from the edge of the hole on both the sides of the bolted hole, which result from the cold expansion. As the measurements progressed away from the hole the tensile stresses are observed. Away from the strap, tensile stresses can be observed in the hoop direction which may be attributed to the machining process on the specimen surface which can be seen in Fig 2b. In line 2, measurements were started from the lower edge of the specimen to the center of the specimen as shown in Fig 1b. In line 2, the presence of radial compressive stresses can be observed around the three bolted holes resulting from the cold expansion process. In line 2, the low tensile stresses observed at the beginning of the radial and axial direction measurements may be attributed to intergranular strains from material texture and the variation in the stress-free lattice parameters in both the directions compared to the hoop direction. In both the measurements i.e. Line 1 and Line 2, residual stresses owing to strap bonding are very low and have no significant effect on the cold expansion stresses.

## Conclusions

In this study, a single strap butt joint and a manhole coupon specimen were reinforced with GLARE bonded crack retarders and the effect of thermal residual stresses on cold expansion stresses have been determined by using neutron diffraction.

1. The high temperature adhesive curing used to bond the strap onto the specimens resulted in the development of low tensile residual stresses in the aluminium substrate. There is a variation in the residual stresses through the substrate thickness, with the residual stresses being higher on the reinforced side.

2. The cold expansion process resulted in radial compressive stresses around the bolted holes. The residual stresses were higher in the outlet face and lower at the inlet face.
3. Thermal residual stresses owing to the strap bonding process have no significant effect on the cold expansion stresses. The use of bonded crack retarders should not, therefore impair the benefits of cold working of fastener joints in aircraft structures.

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| **Material** | ***E*/GPa** | **Ultimate tensile strength (MPa)** | **0.2%Tensile yield strength (MPa)** | **CTE/$10^{-6}$ °$C^{-1}$** |
|---|---|---|---|---|
| AA 2624-T351 | 71 | 434 | 331 | 23.6 |
| GLARE 6/5 | 66 | 1214 | 360 | 23.6 |
| FM94 | 1.9 | - | - | 58 |

Table1. Mechanical properties of materials used in this investigation

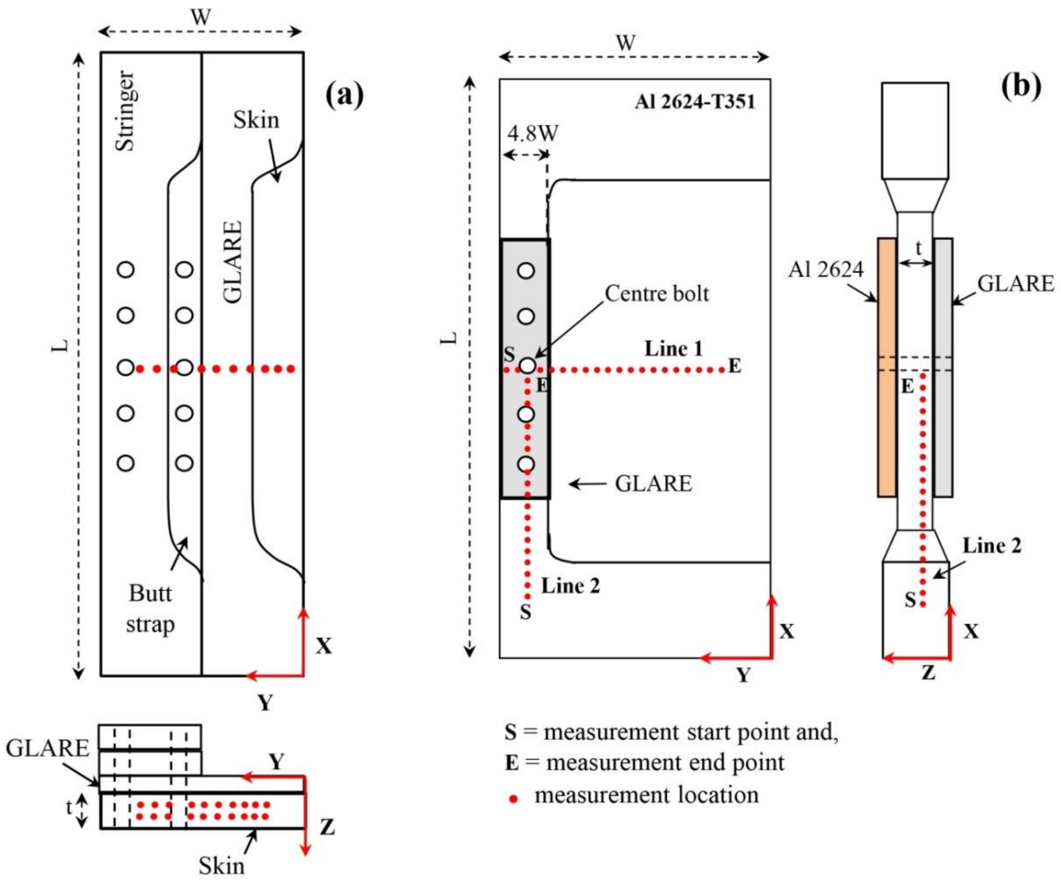
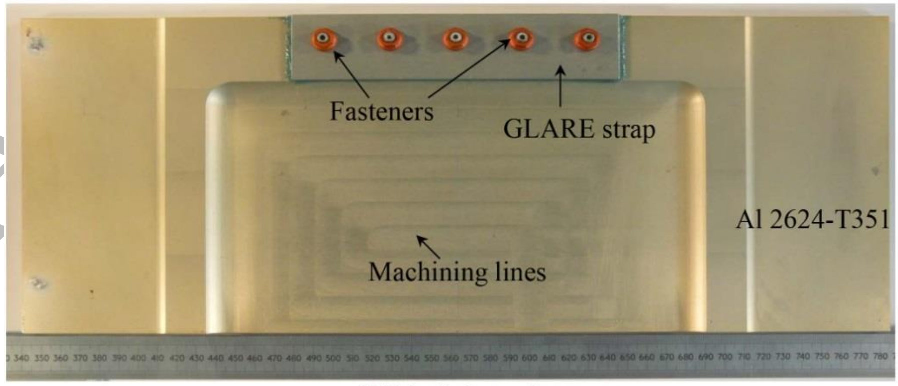


**Figure 1**. Geometrical details of (a) single strap butt joint and (b) manhole specimens

**(a) Single strap butt joint specimen**



**(b) Manhole specimen**

**Figure 2**. Actual specimens used for investigation

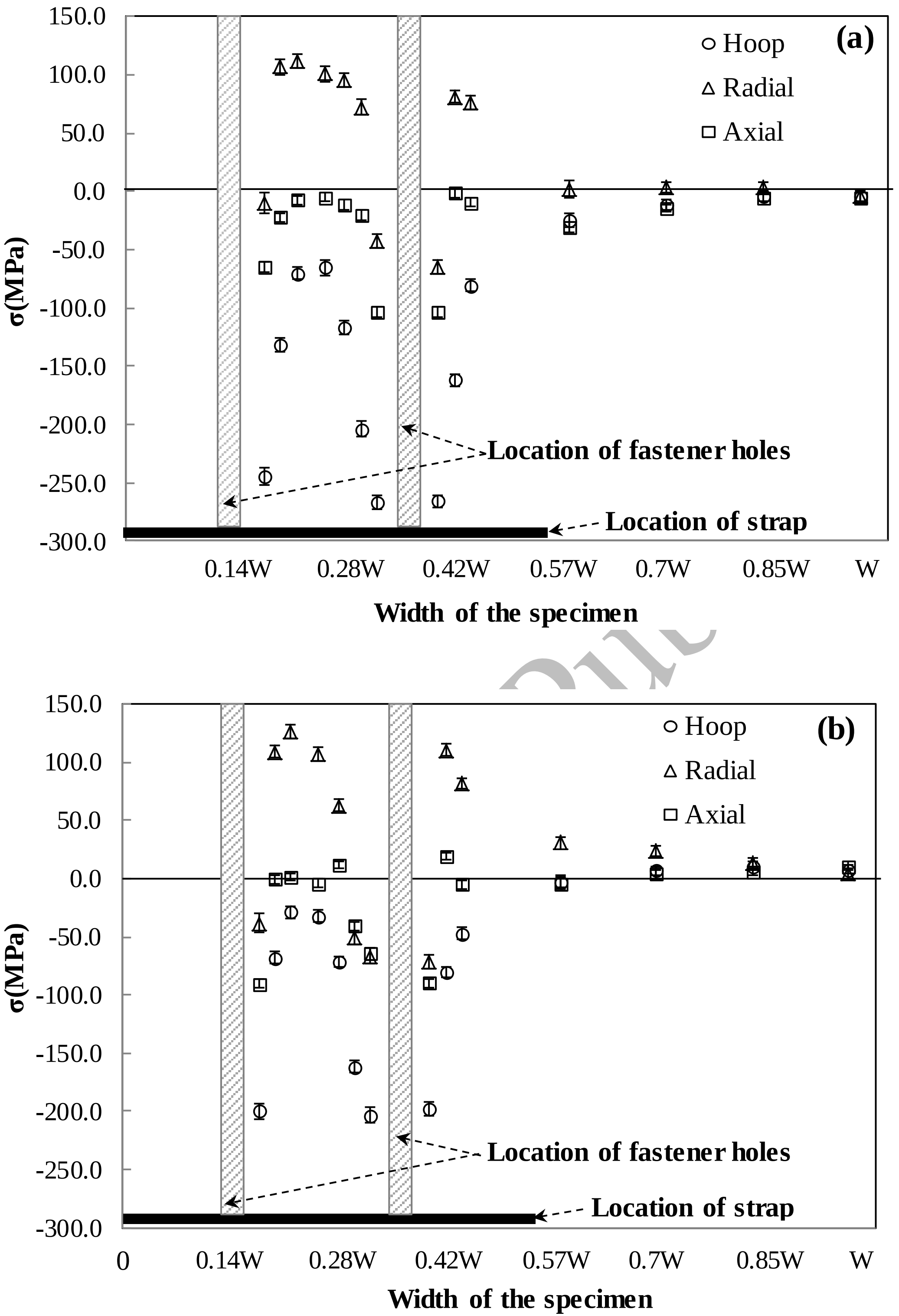


**Figure 3**. Residual stress distribution in single strap butt joint skin plate (a) 0.27t (b) 0.625t from reinforced side

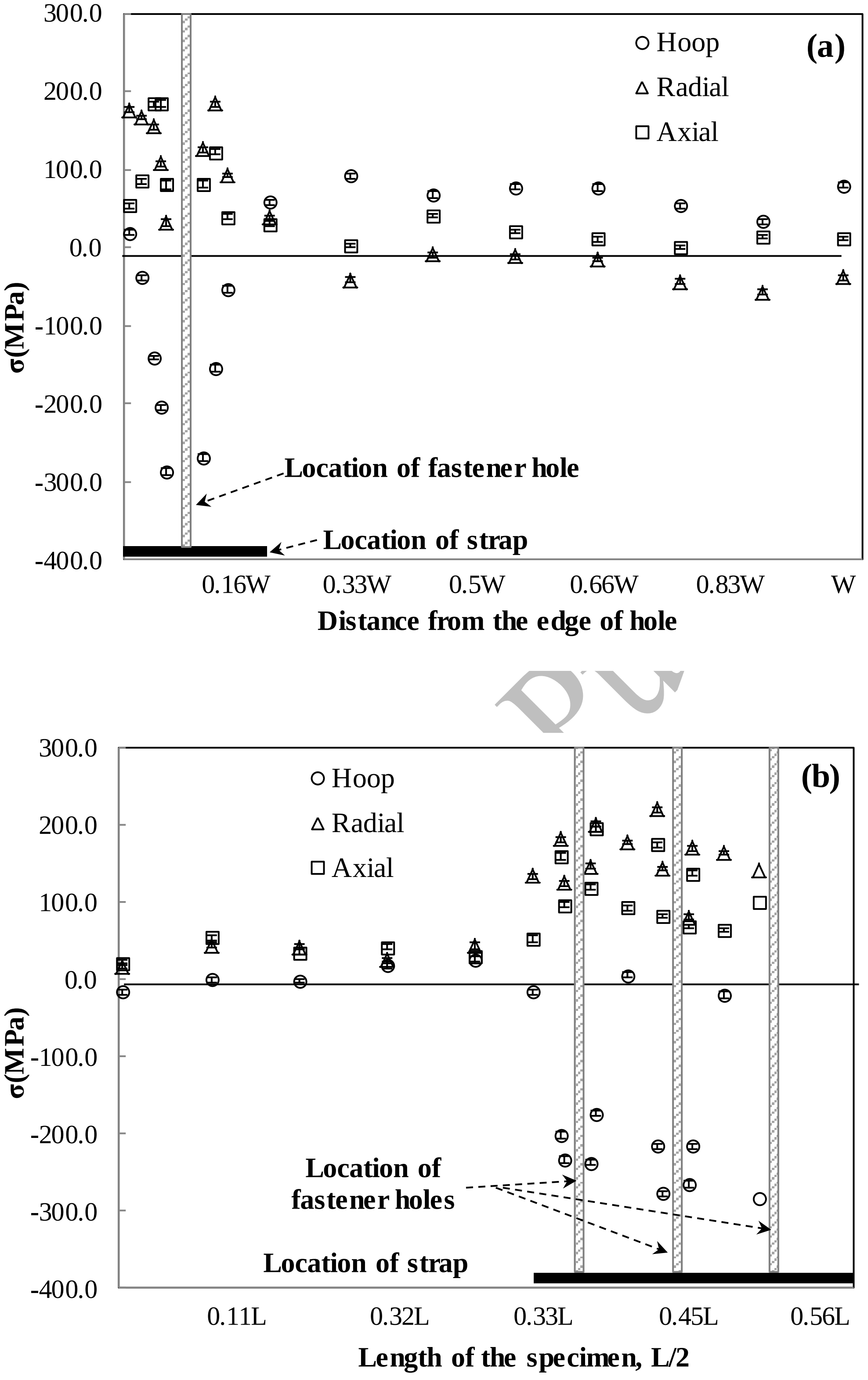


**Figure 4**. Residual stress distribution in manhole specimen (a) Line 1 (b) Line 2