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F-16 Engine access cover and ventral fin structure analysis model for evaluation of life enhancing modifications

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INTRODUCTION

The Royal Netherlands Air Force (RNLAF) operates F-16 fighters in a mix of block 10 and block 15 versions.
A long-term reliability and maintainability problem for the F-16's are the ventral fins and the engine access covers on which the ventral fins are mounted.
The aerodynamic surrounding of the ventral fins produces large amplitude aerodynamic loads that result in: fin failure, engine access cover fatigue cracks, and wear at the fin-cover interface points.
Replacing the block 15 fins with modified block 40 fins is expected to eliminate the fin failure problems. The block 40 fins are mounted on the existing block 10/15 engine access covers. A flight test program has shown that a block 40 fin with Metal Matrix Composite (MMC) skins and a more rounded shape of the leading edge ("nose cap") is the preferred fin configuration. This fin significantly reduces the aerodynamic loads in the cover structure. It is the intention to gradually replace the older types of ventral fins with these new block 40 fins.

DESCRIPTION OF STRUCTURE

The lower half of the ventral fin fuselage section consists of a fixed part and two removable stiffened panels: the engine access covers (fig. 1). The ventral fins are mounted on these engine access covers.

The engine access covers (fig. 2) basically consist of a skin with chemically milled pockets. Four crescent moon shaped frames with a z-shaped cross section stiffen the skin panel. The port and starboard covers are not identical. This is mainly caused by large access hatches in both covers.

The ventral fins are in fact sandwich panel structures. The sandwich panel is solid at the leading-trailing and lower edge. The top edge reinforcement is a root rib. At roughly half the chord a vertical beam reinforces the fin. This beam forms one integral part with the main fitting of the fin. This fitting directly connects to a bracket on a heavy fuselage frame.

This fitting will transfer the bulk of the load from the fin to the fuselage. The fin torsion and side load (perpendicular to the fin plane) can also be transferred by bolt connections to the four z-section stiffener frames on each of the covers.
The bolt connection points are referred to as "shear ties", as the torsion and side load will primarily cause shear loads on the bolts. A typical shear tie is presented in fig.3. Note that the bolt head rests on a ring. This ring rests directly on the flange of the z-stiffener on the cover.

Although originally not intended as such, the shear ties can transfer a significant amount of side bending moment from the fin to the cover structure. The bending moment is transferred by a tension load in the bolt and a contact load at the edge of the fin root (fig. 4).

PROBLEM DESCRIPTION

Replacing the block 15 fins with modified block 40 fins strongly reduces the fin structural problems. However, engine access cover wear and fatigue caused by fin aerodynamic loads is still expected to be a significant durability problem. The problem is intensified by the introduction of intake mounted pods. These cause a vast increase of the duration of exposure to high fin aerodynamic loads.

A survey of service experience showed that the shear ties are the critical locations and provided additional information of locations and occurrence of fatigue damage. The service experience of three different airforce bases is summarized below:

Chaffing (wear of the skin outer surface) occurs near the forward shear tie bolts. At one base once every three weeks panels with ovalized forward shear-tie bolt holes are repaired. These types of wear are strongly reduced by frequent checks for lose bolts.
These types of wear usually occur in combination with fatigue cracks along the neck of the z-stiffener near the bolt head. Cracks are regularly found in the forward z-stiffener (fig. 5.a). At one base roughly 10 z-stiffeners per year are replaced for this reason. Cracks up to 4 inches in length have been found. These cracks do not return after repairs where a part of the worn out skin is replaced and a doubler is introduced.
At a lower rate cracks are found in the other z-stiffeners as well.
At one base about four times a year a crack is found in the engine access cover skin near the forward shear tie bolts (fig. 5.b). Cracks have been found at the ends of the z-stiffener in the flange to web radius near the cover skin.

One mechanism that causes fatigue damage appears to be bending of the skin and the z-stiffener flange near the bolt hole. This is illustrated in fig.6. Note that skin cracks occur where the skin bends around the bolt head and ring. The z-stiffener cracks due to high local bending loads along the bolt head edge.

No evidence exists of fatigue damage in the heavy fuselage frame near the connection to the main ventral fin fitting.

In view of these problems a project was defined within the framework of the Commercial Operating & Service Savings Initiative (COSSI) program. Main contractor for this project is DWA Aluminum Composites.
The objective of the ventral fin project is to propose and evaluate simple structural modifications for the F16A/B block 10/15 engine access covers. This involves three steps:

- The development of a finite element model that serves as a tool to evaluate engine access cover modifications.
- The processing of flight test data in order to obtain in-flight load levels and to identify critical locations in the structure.
- The evaluation of possible modifications at critical points in the structure.

DEVELOPMENT OF ANALYSIS MODEL

The engine access cover finite element model was constructed from aerodynamic contour data and a limited set of production drawings. The model for the basic block 40 fin was obtained from Lockheed Martin Tactical Aircraft Systems (LMTAS).

First a coarse mesh model was developed (fig. 7). This model covers the block 40 MMC skin fin with nose cap that is fitted on a block 10/15-engine access cover. The finite element model has been tuned and validated by comparison to static and dynamic test results.
The model results show good correspondence with ground vibration test results and sufficient correspondence with the static calibration test results for fin root bending strains. It was decided that this model provides a good basis for further analyses.
The correspondence of measured and computed strains on the engine access cover is very poor for most strain gauges. This is caused by unfortunate strain gauge locations. The one strain gauge placed directly on an active load path agrees very well with the test results. As the following analyses focus on engine access cover stresses, it was considered desirable to acquire additional reference data.

A new static calibration test has been conducted on a block 10/15 engine access cover with block 40 MMC skin fin with nose cap. These tests are not part of the current investigation. These tests are conducted as a part of the intake mounted pod flight test program of the RNLAF. This test provides an additional check on the computed cover strains. The results have not been processed yet. First indications are that significant strain levels occur at the selected strain gauge locations. At the key locations agreement between calculated and computed strains appears to be fairly good.

The coarse mesh finite element model does not provide enough detail at the shear tie bolts. A refined model (fig. 8) was created near the port forward shear tie. This improves the prediction of the stress levels at the stress concentrations that cause the fatigue problems in the cover stiffeners and the cover skin.
The refined model proves to be a useful tool for evaluation of cover stress levels.

FLIGHT LOAD LEVELS

The extreme root bending moment levels of the fins have been derived from time signal recordings. This was done for each of the three most relevant root-bending locations on each fin: the forward shear tie, the aft shear tie and the main fitting. Only the first bending mode and the first torsion mode of the fin are considered. These dominate the fin root bending strain signals.

The resulting fin root bending moment levels are summarized in the table 1. Data is presented for two fin configurations that were subjected to a flight test program: the basic block 40 aluminum skin fin and the MMC skin fin with nose cap. The table presents a strain level that is directly related to the bending moment.
Note that for the first torsion mode the introduction of the MMC skin material causes a large reduction of the fin root bending strain at the forward shear tie. This is why the MMC material has been selected for the fin modification. Note that for the engine access cover analysis presented in this paper only the second column is relevant.

The in-flight load data shows that the fin first bending and torsion resonances dominate the fin cover interface loads. The deformed shape of the fins and the covers for these resonances are also available from the finite element model (fig. 9). These are called “mode shapes”. The amplitude of the computed deformations is selected by the analysis code. I.e. the deformed shape is “normalized”. These normalized mode shapes were scaled to in-flight amplitude levels. This in turn produces in-flight stress levels at all points in the model.

The regions in the cover structure around the forward and aft shear tie bolts are identified as critical locations from these results.

DESCRIPTION OF MODIFICATIONS

The refined finite element model was used to evaluate some small structural modifications of the cover structure at the shear tie interfaces. Note that this model represents the original block 10/15 cover with a MMC skin fin with nose cap.
Four modifications of the engine access cover structure are presented here. The corresponding four finite element models have been derived from the refined model.

Two existing modifications are presented:

1. *The RNLAF airforce modification of a standard (i.e. no brackets at shear ties) block 10/15 cover (see fig. 10):*
   This modification consists of a hardened cres strip attached on top of the z-stiffener flange. The ring below the bolt head rests on the top of the cres strip. The main aim of the modification is a reduction of the bearing load and a simultaneous increase of the bearing allowable. To this end the part of the cres strip at the bolt hole acts as a cylindrical bushing that sticks through a hole in the skin. See fig. 10. The modification also reduces the fatigue problem since adding the cres (doubler) strip effectively increases the thickness of the z-stiffener flange.

2. *The Lockheed modification consisting of brackets at shear ties on block 15 covers (see fig. 11.a):*
   The brackets are made of aluminum. This does not solve the bearing problem. Bracket bolt holes still ovalise and wear-out. This modification does substantially reduce the fatigue problem since a large part of the bolt load is now transferred to through the brackets. That is: the z-stiffener flange bending is reduced The bracket also reduces the strong curvature of the skin near the bolt. The skin now also has to bend around the side of the base of the bracket, instead of bending around the bolt head only (see fig. 6).

Two proposed modifications are presented:

3. *A modification based on the RNLAF modification (see fig. 12):*
   The cres-plate is replaced by a cres L-section. Basically the thicker L-section base provides more bending stiffness. It also attracts more load since the base is now directly connected to the web of the z-stiffener. Finally the L-section provides more bending stiffness in the direction along the z-stiffener. This allows the bending load in the shear tie connection to be partially short-circuited within the L-section.
4. *A modification consisting of an improved bracket (see fig. 11.b):*
   This modification consists of the Lockheed bracket with a wider and twice as thick base resting on the z-stiffener. The base now is as wide as the fin root contact patch at the forward shear tie. The bending is introduced into the cover by the combination of the bolt load and a contact load at the edge of the contact patch of the fin. The wider bracket base short-circuits the resulting in-between shear load within the bracket. This reduces z-stiffener flange bending significantly. In the model the thickness of the bracket base has been doubled as a quick method to increase bending stiffness in the direction along the z-stiffener. However, a much lighter solution can be obtained if vertical flanges in a direction parallel to the z-stiffener are introduced.

COMPARISON OF EFFECTIVITY

In-flight load levels cannot be used for the comparison. The change in interface stiffness may affect the deflection of the fin. This in turn affects the aerodynamic loads. The change in load level is impossible to predict as the source and the exact level of the disturbances in the airflow is unknown.
What is needed is a known static load that causes deflections similar to those of the 1st torsion mode.
The 1st torsion mode dominates the loads at the forward shear ties. The deflection of this mode suggests that the aerodynamic loads will mainly act near the leading edge of the fin. This resembles one of the static calibration load cases: a load pressing on the fin surface near the leading edge in outward direction.
The maximum principal stresses were computed for this static calibration load case. This was done for all four modifications. Only the stresses at the port forward shear tie were considered.

In this way the stresses for equal external load levels can be compared.
Table 2 summarizes the maximum principal stress results of the static calibration load case for all models.

Considerable reductions of stress levels can be obtained with all modifications. The best results are obtained for the improved Lockheed modification. However, the L-section modification also provides a very substantial improvement. The latter solution requires less complicated machining operations. More important is that the L-section modification also boosts the bearing allowable for the bolt loaded in shear. This reduces bolt hole wear, and might be applied (in part) at the starboard forward shear tie. The current LMTAS modification does not improve the bearing allowable as much as the L-section modification.

CONCLUSIONS

A calibrated finite element model of the engine access cover and the ventral fin area was created. Strain gauge data measured during flight tests were used to derive in-flight load levels. That is: the amplitude of the dominating vibration modes was obtained. These modes are also available from the finite element model. Stresses in the cover structure are obtained by scaling the computed modes. Critical locations in the cover structure were identified on the basis of these results. The critical locations are the forward and aft shear tie connections on both engine access covers.
These locations agree with data from service experience.
Two existing modifications of the shear tie structural detail are evaluated with the finite element model. Slight modifications to these existing modifications are proposed. All modifications provide significant stress reductions.

The NLR has conducted all ground tests, prepared and did the data collection and processing for all flight tests. The NLR also did the analyses and some engineering work on the modifications. Hence, this project also shows that the NLR can provide the full range of services in such an investigation.

ACKNOWLEGEMENTS

The project described in this paper was awarded by the main contractor DWA Aluminum Composites as contract nr. A04451. The project was defined by the COSSI program management of the USAF.
The RNLAF performed all test flights and ground tests in cooperation with the NLR and LMTAS. The RNLAF kindly initiated a service experience survey at several of its air bases.
LMTAS provided the fin finite element model.

Table 1 Bending moment related strain results for relevant fin-cover interface locations for a throttle chop at M=0.95 and 50000 ft

Mode shape	location	Bending moment related strain amplitude ** (μ strain)	
		ALU skin fin	MMC skin fin + nose cap
1st Bending mode	Aft shear tie, port	180	175
	Aft shear tie, stbd	180	120
1st Torsion mode	Fwd shear tie, port	275	180
	Fwd shear tie, stbd	275	210
	Main fitting, port	1050	1220
	Main fitting, stbd	1170	*

* = bending mode interacts with torsion mode
** = amplitude computed with:
½ * (maximum peak level in time slice – minimum peak level in time slice)

Table 2 Summary of reduction factors for static calibration load case 233 maximum principal stress results in the port cover z-stiffener flange at the forward shear tie

model	reduction in stress level w.r.t. basic model (w.r.t. Lockheed mod.) %	ratio: basic model stress/modification stress
Basic refined model	0	1.0
RNLAF modification (CRES plates)	62	2.7
Lockheed bracket	75 (0)	4.0
L-section CRES	82 (28)	5.5
Modified bracket	86 (44)	7.1

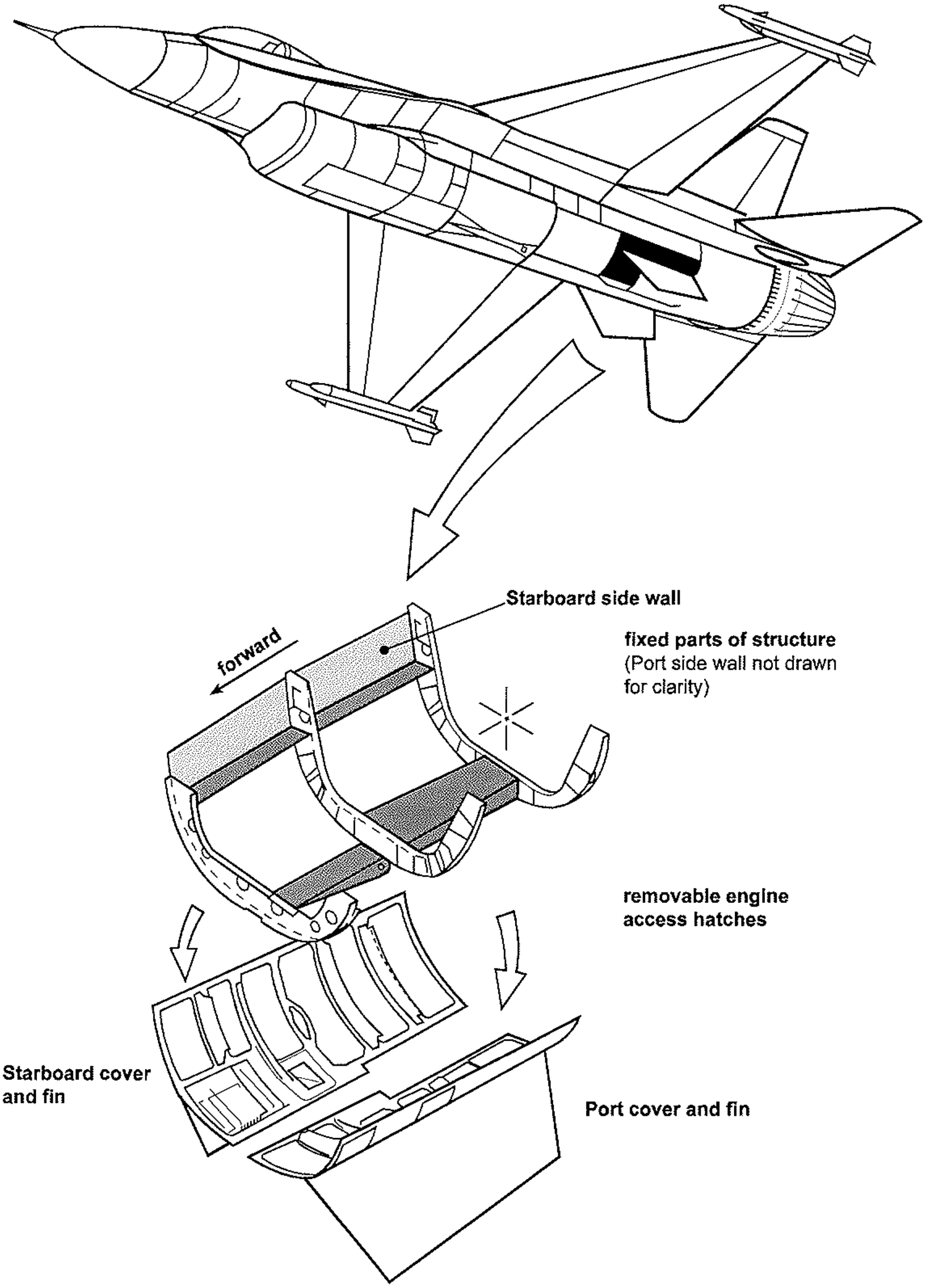


Fig. 1 Exploded view of the lower half of the rear fuselage ventral fin section

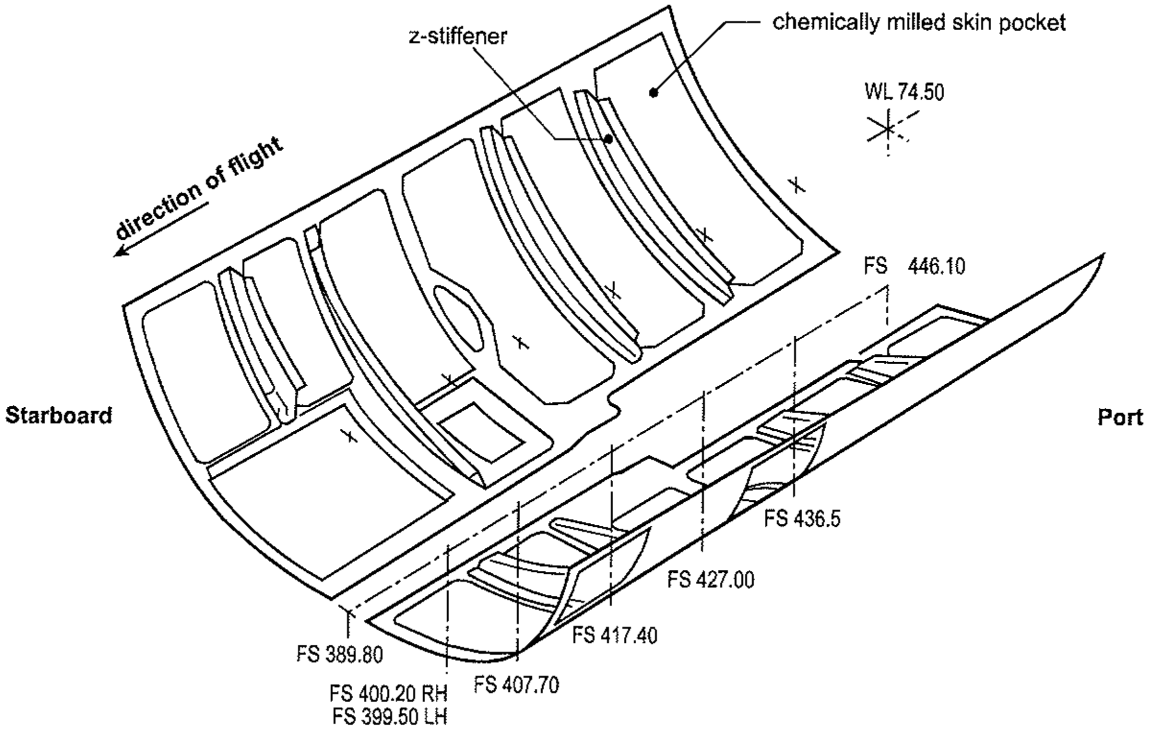


Fig. 2 Port & starboard engine access covers

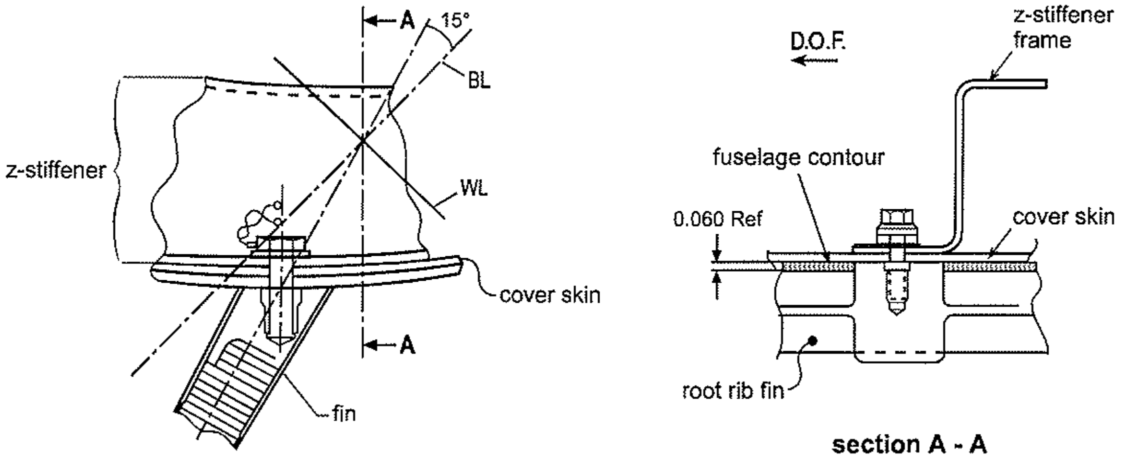


Fig. 3 Typical "shear tie" fin to engine access cover connection

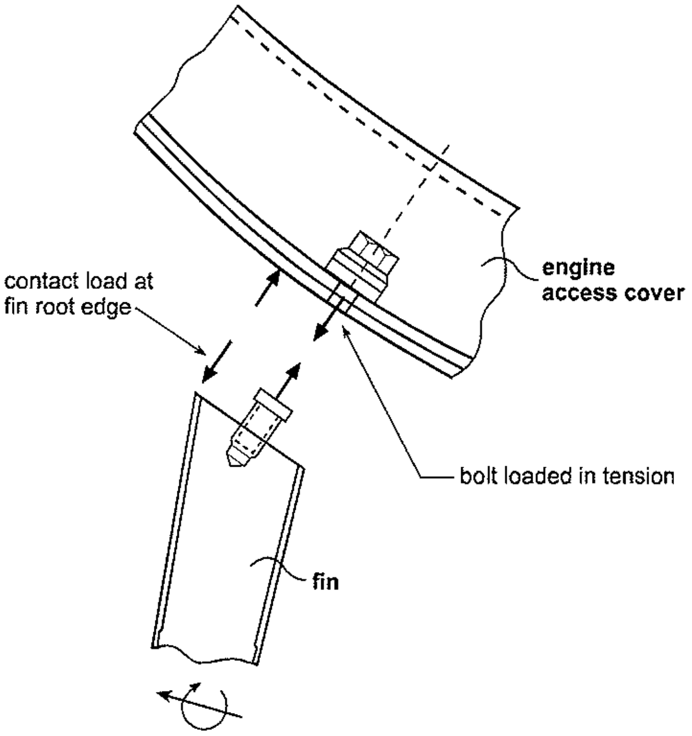
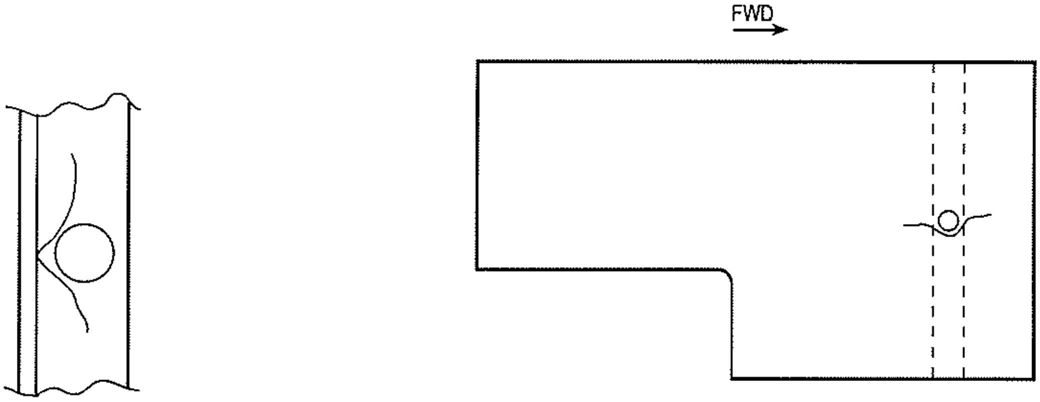


Fig. 4 Transfer of bending loads from ventral fin to cover at a typical shear tie connection



a) Volkel AFB, crack in z-stiffener flange

b) Volkel AFB, crack in cover skin

Fig. 5 Fatigue damage reported in a survey of cover problems at three RNLAF airforce bases

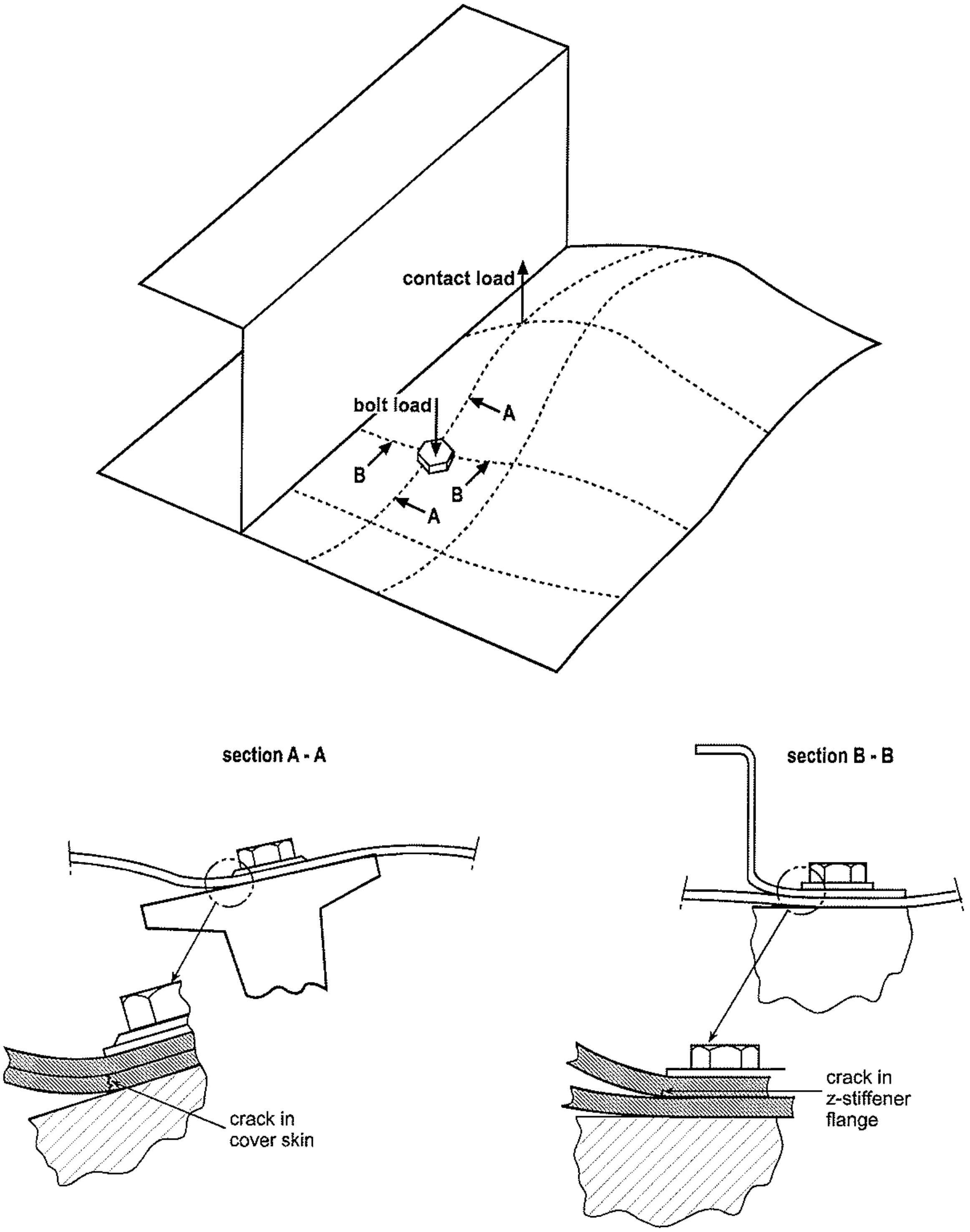


Fig. 6 Mechanisms causing the fatigue problems illustrated in figure 5a and 5b

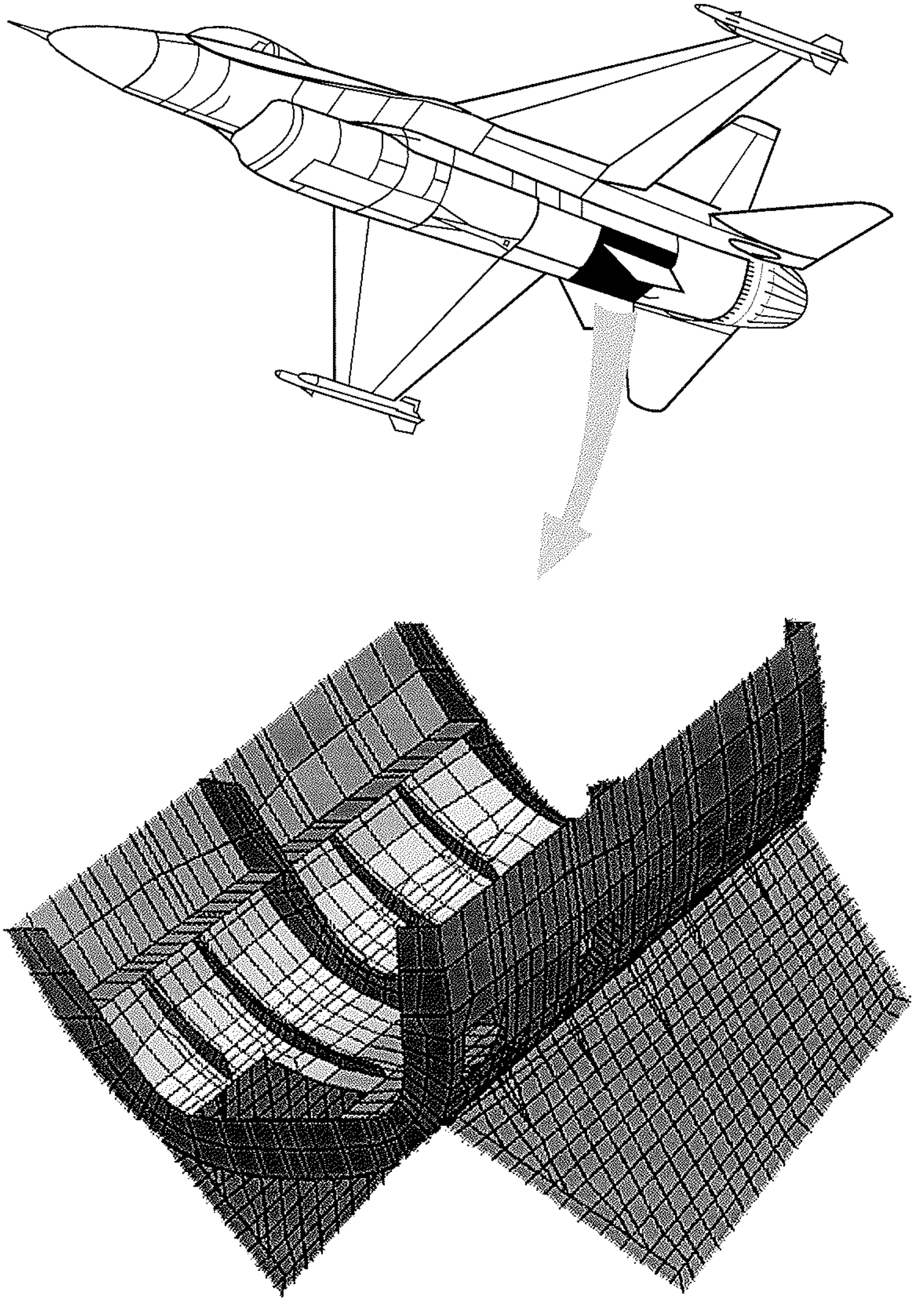
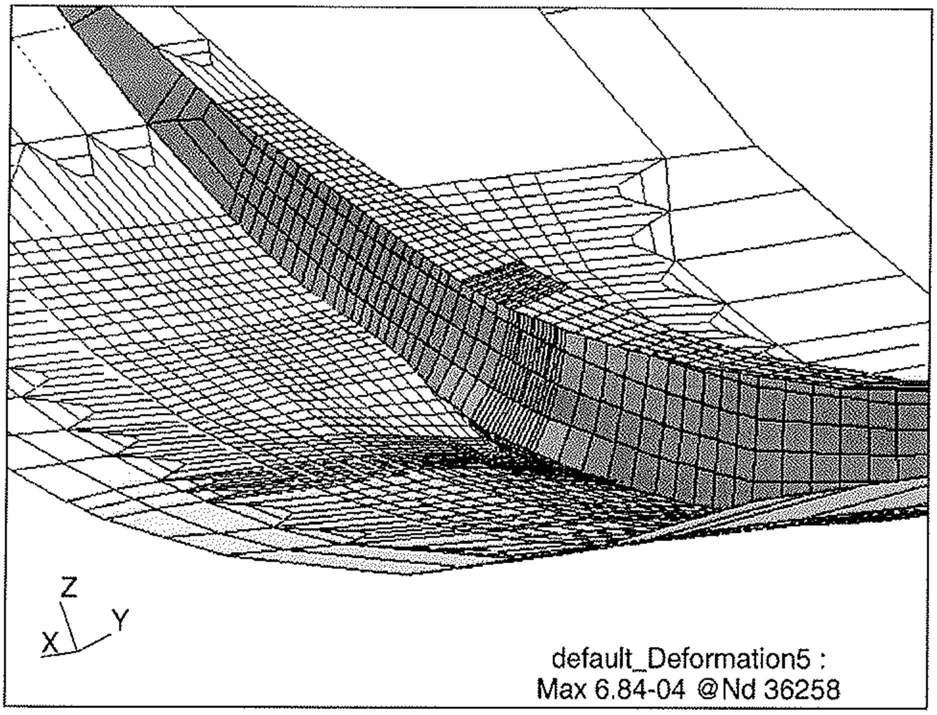
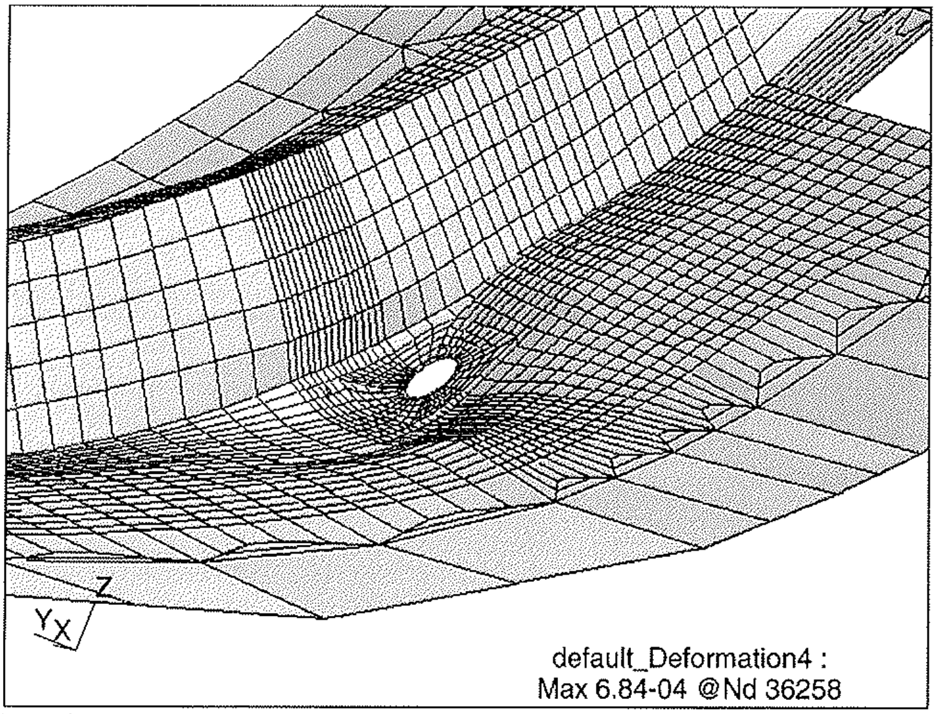


Fig. 7 Structure covered in model

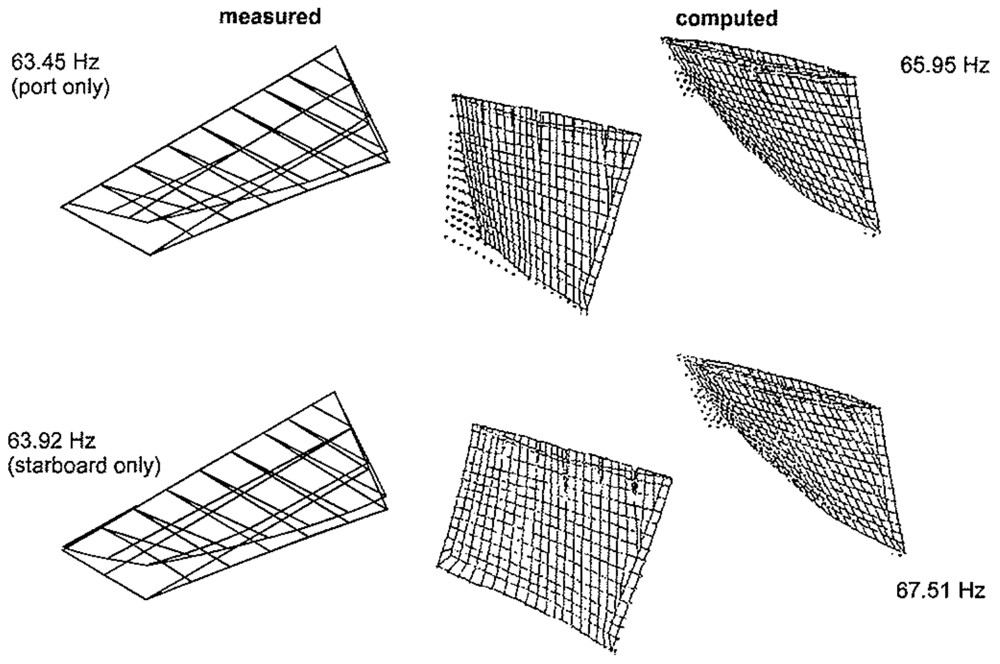


a) Deformed shape (note separation of cover skin and z-stiffener flange)

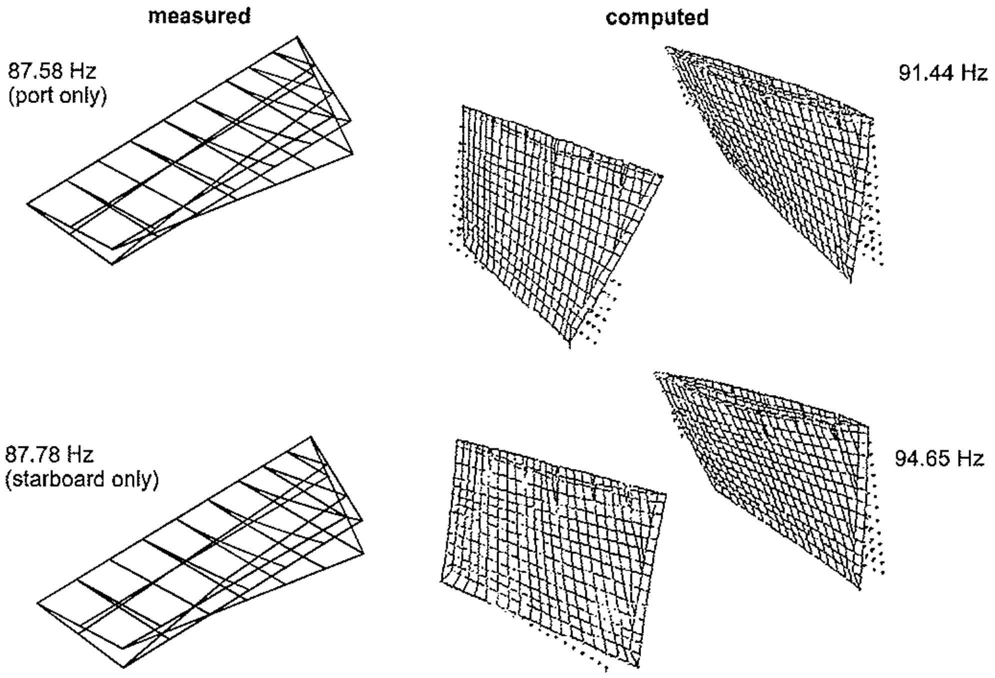


b) Deformed shape (note wave pattern around rigid bolt head, open hole = rigid bolt head)

Fig. 8 Views of parts of the refined mesh model near the port forward shear tie

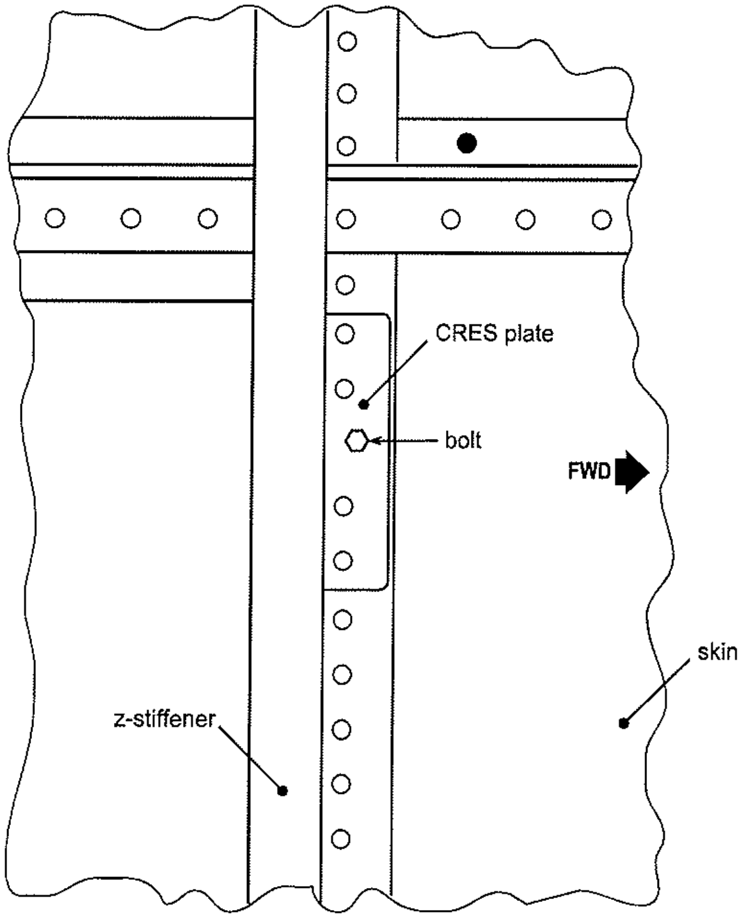


a) Comparison of computed and measured 1st bending mode shapes

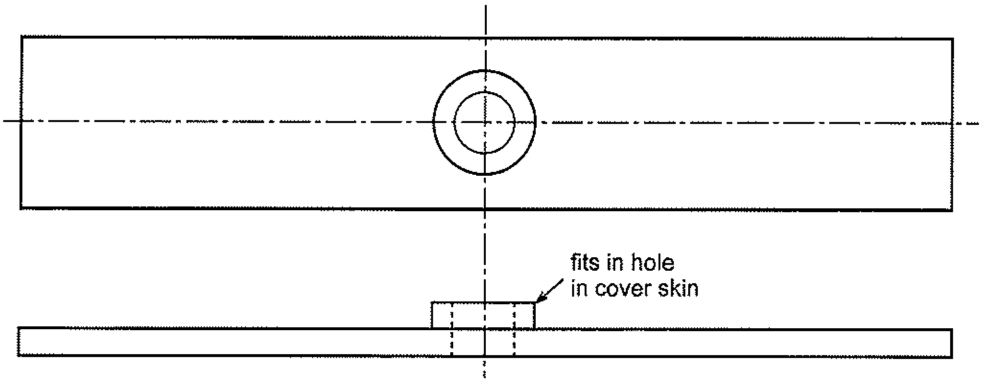


b) Comparison of computed and measured 1st torsion mode shapes

Fig. 9 Relevant examples of measured modes data and the corresponding computed mode shapes for the MMC skin fin with nose cap

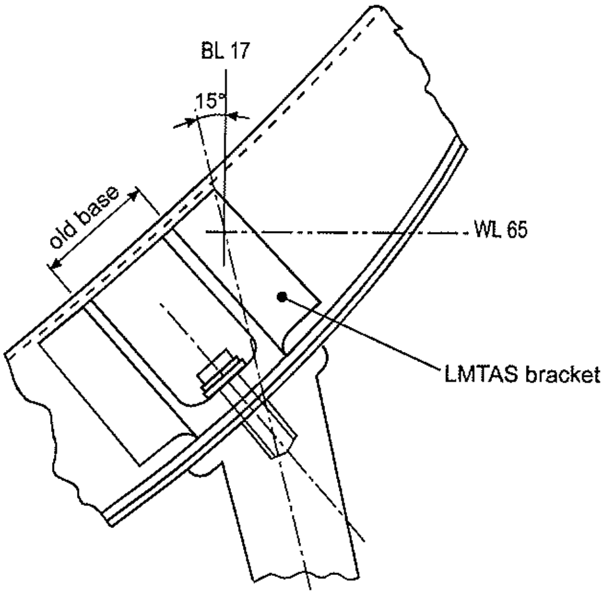


a) Typical inside view of cover at shear ties

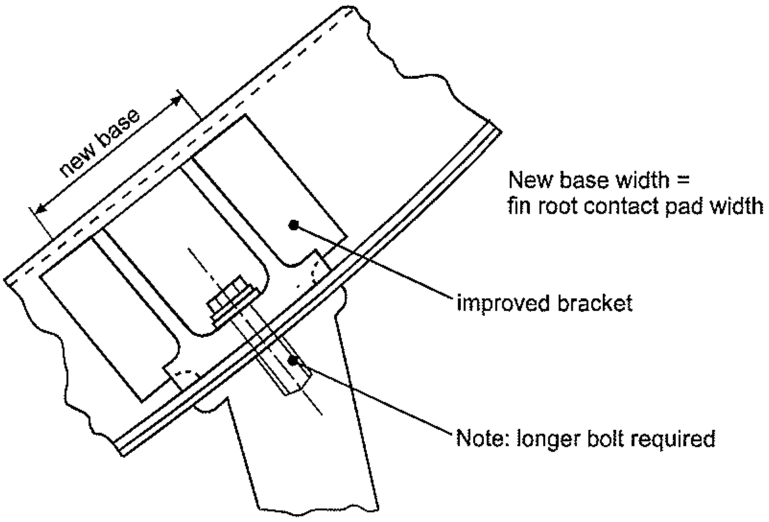


b) Corrosion resistant steel (CRES) plate

Fig. 10 RNLAF modification

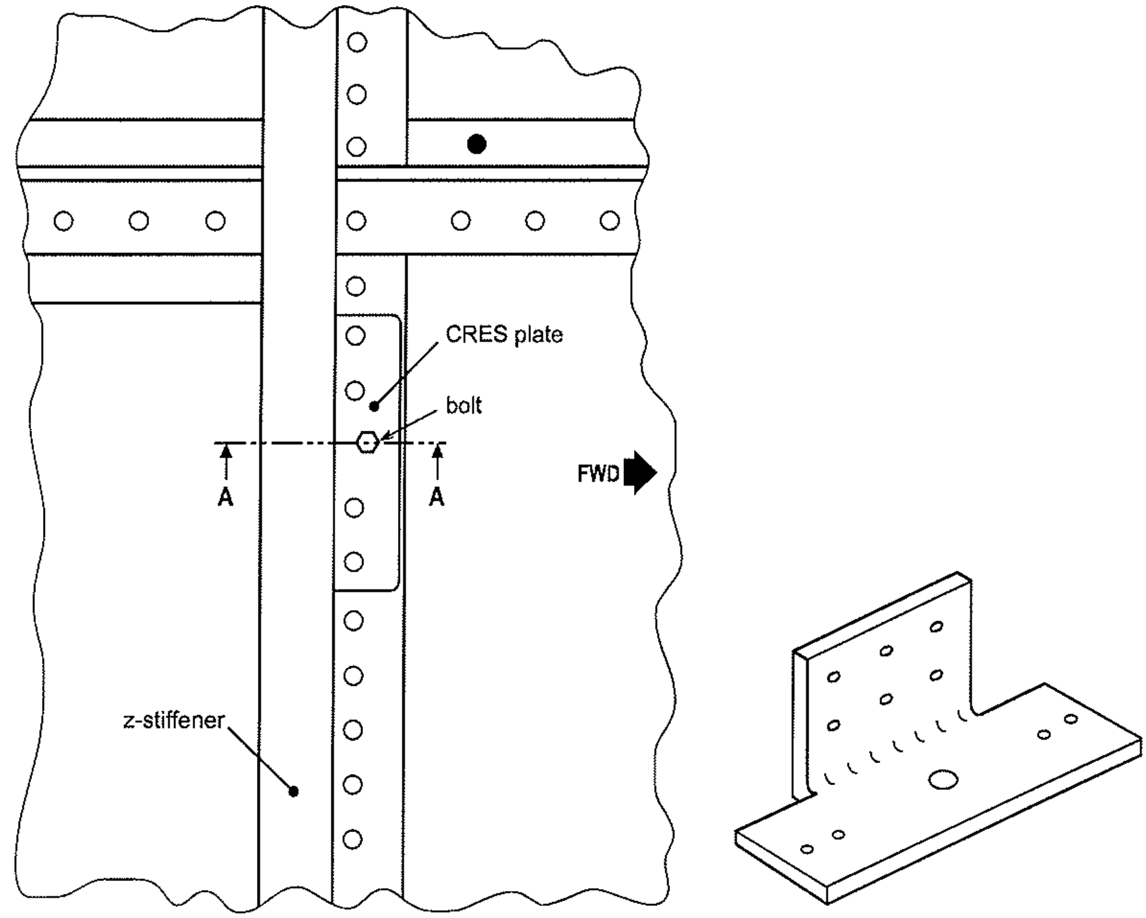


a) Original LMTAS bracket



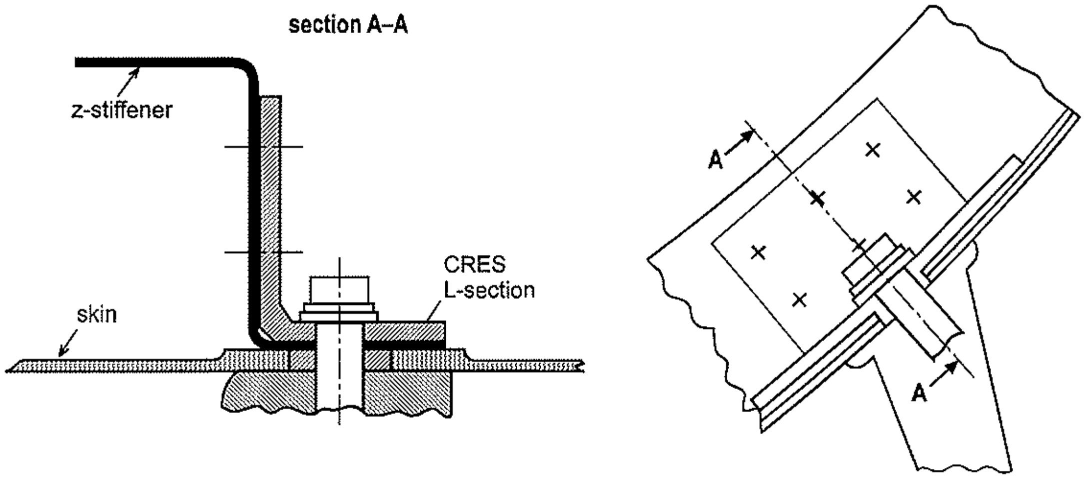
b) Modified bracket with thicker and wider base

Fig. 11 Improved bracket based on LMTAS modification



a) Typical inside view of cover at shear ties

c) L-section, CRES “bracket”



b) Section A–A

Fig. 12 Improved RNLAF modification using L-section instead of strip