Design of Lugs

An increasingly pragmatic and cost-effective approach to material selection and testing.

Designers of aerospace components such as lugs, tension clips, bath-tub fittings etc. are taking an increasingly pragmatic view of material selection. There is an increasing awareness that the availability of specific material property data has been an 'after thought' in many projects. In some cases, a very costly test programme is then quickly performed to provide data that then have to be validated for approval by the certification or regulatory authorities. A trend has been noted where the availability of validated (specialised) material properties increasingly dominates material selection.

Companies and organisations that generate such data may also note this trend and anticipate future demand for their services by examining the validated design and analysis methods available to their clients' designers.

Validated design of lugs

Aerospace designers must approach the design of components such as lugs using a validated method that is acceptable to the FAA, EASA, CAA etc.

For 80 years, ESDU by IHS Markit (www.ihsesdu.com) has developed and validated a series of documents (known as Data Items) supported by software that present detailed analysis, design and testing methods and data used in aerospace, mechanical, chemical, civil and structural engineering applications. There are currently eleven ESDU Data Items (and one computer program) on lugs that present the various engineering 'methods' needed to analyse the static and fatigue strength; included are stress intensity factors and stress concentration factors of lugs. The Data Items are all supported by practical design guidance and data from material and component testing.

Elements of these methods (summarised in ESDU Memorandum 81[1]) were originally developed in individual companies such as Boeing, Lockheed, Westland Helicopters, Fokker and various companies that are now part of BAE Systems. Aerospace designers from all of these companies, and the majority of all other organisations engaged in aerospace design, now use the ESDU methods.

Engineers from the regulatory bodies, such as the FAA and CAA, are members of the independent, unpaid committees of experts that validate all ESDU Data Items.

Lug design using ESDU methods

Data Items ESDU 91008[2] (Strength of lugs under axial load) and 06021[3] (Strength of lugs under transverse load) and ESDU 08007 (Strength of lugs under oblique load) include strength analysis of the lug under in-plane axial, transverse or oblique loading from a clearance fit pin. See Appendix A for sample pages from ESDU 91008 and ESDU 06021. Other ESDU methods evaluate the stress concentration due to the hole, the stress due to an interference-fit bush, the endurance of a lug under repeated loading and the stress intensity factors for cracks in loaded holes (when damage tolerance and/or component life using fracture mechanics is appropriate).

Material selection

'Conventional' (linear elastic) stress analysis is usually carried out using finite element analysis (FEA) software. This method of stress and deformation analysis only requires 'common' material properties - approved for aerospace use - such as Young's modulus, Poisson's ratio, yield strength etc. These are readily available from either MMPDS[4] or MMDH[5].

Typically, an aerospace designer will specify a material recommended by the company's material specialists, for which the buying department has identified a ready supply at what is considered a "reasonable unit cost". But when it comes to the design of components such as lugs, this policy has often led to a crisis when it is realised - too late - that conventional linear elastic FEA assuming isotropic material properties is not sufficient for certification.

The static lug strength analysis in ESDU 91008 includes the effect of the material grain flow direction and whether the lug will be fabricated from sheet, casting, bar, extrusion, forging etc.

Design of Lugs assisted by the ESDU engineering service

A crucial part of the ESDU engineering service, which comes as part of an ESDU subscription, is that designers, engineering analysts and materials scientists within the client company may speak with the ESDU Engineers that draft and develop all ESDU Data Items and their associated software. This is a vital support, particularly when a designer is unfamiliar with the specifics of a specialised analysis or uncertain of the expected accuracy, applicability and assumptions used in the calculations.

ESDU has always received and satisfied many requests for the less common material properties for the wide range of materials, including those found in the MMPDS and MMDH handbooks. To determine the static strength of a lug using the validated methods summarised in ESDU 91008, the following properties are required:

Airbus A300 rudder hinge lug

For the lug:

- Young's modulus
- Ultimate longitudinal (in-grain) tensile strength
- Ultimate transverse (cross-grain) tensile strength
- 0.2% longitudinal proof stress
- 0.2% transverse proof stress
- 1.0% proof bearing stress (b_{10})
- Material elongation

and for the pin:

- Allowable shear stress
- 0.2% proof stress

Examination of MMPDS and MMDH data shows that specific longitudinal and transverse tensile (rupture) strengths and the bearing strength are often unavailable for candidate materials. Further, an evaluation of the fatigue life (endurance) of the lug, and the crack growth rate for 'through thickness' or corner cracks, is usually required. But, if the designers feel so strongly about the desirability of selecting a material for which an S-N curve is not commercially available, it typically costs (in 2007) approximately $250,000 (£180,000) to generate enough data for that single, specific material specification.

Consequently, it has always been common for ESDU's clients to ask for an S-N curve to determine the endurance of the lug - ESDU has over 110 such curves! The ESDU engineers have noticed recently, however, that many designers now understand that the cost of acquiring such specific data will dictate the material selection.

A new trend in specifying lug materials – case study

One client requested data from ESDU for the 'missing' material properties for L110 aluminium alloy. The company had found a good local, reliable, low cost supply of the material as a forging and MMDH gives values for Young's modulus (70 GN/m^2), Poisson's ratio (0.33) and elongation (0.8%). The handbook also states that, except for flame welding, its 'weldability' is 'very good' and that it is not susceptible to corrosion.

Understandably, therefore, the designers had already developed their lug design and used FEA to estimate stresses for the range of applied (oblique) loads. Unfortunately, on consulting ESDU 91008, they discovered that it is not acceptable simply to compare their estimated maximum stresses with the material yield (or proof) strength quoted for L110 when designing a lug for an aerospace application. Further, when they attempted to use the ESDU method, they found that only the longitudinal 0.2% proof stress is quoted for L110 in the MMDH handbook and no data are given for the proof bearing (b^{10}) stress. No S-N curve is available either! The engineers were therefore considering the development of a test programme to provide their own values for (b^{10}) and the all-important S-N curve.

First, the ESDU engineer recommended that they examine ESDU 97024[6] (Derivation of endurance curves from fatigue test data, including run-outs) for guidance on the design of the fatigue tests, subsequent derivation of a valid S-N curve and (the vital) assessment of how representative that curve is. Computer program W9724 accompanies this Data Item to perform the necessary curve-fitting computations and plot the derived curve. Typically, material tests are carried out in batches of (say) ten, a revised S-N curve is generated and its expected accuracy rapidly and consistently assessed. This means that the number of tests can be minimised to keep costs down. Using ESDU 97024, another ESDU client required only 40 test specimens to generate the required curve whereas the five S-N curves included in ESDU FAT E.07.01 are each derived from an average of 700 fatigue tests!

Even so, the clients concluded in this project that embarking on a fatigue test programme was still going to be prohibitively expensive for them and, critically, it would have taken too long to organise and carry out. The ESDU engineer therefore suggested that they re-consider their material selection and pick a material for which the required data are available!

ESDU 91008 presents all of the necessary (and validated) material properties for the following lug materials:

Aluminium alloy	L168 (formerly L65)
Aluminium alloy	DTD5124 (formerly DTD5074)
Steel	S154 (formerly S96)
Steel	AISI4130 (formerly S96)
Titanium	BS2TA10

Although the unit cost was greater than that for L110, the client discovered that a reliable source of L168 aluminium alloy was also available but soon realised that the immediate availability of all the data required to get their lug design approved meant that it was a vastly lower overall cost. Equally vital, there would be no project delay for the tests on the original L110 choice!

The implications of this trend for Aerospace materials engineers

A commercial material testing business (or a test facility within an aerospace company) must obviously gather data useful to designers. From the material selection trend noted in this article, it is apparent that such materials engineers will gain from examining aerospace design methodology to anticipate what data they should collect to fill the gaps in material property data. This is particularly true of any material in the MMPDS and MMDH handbooks that might be considered for the design of components subjected to fatigue loads - such as lugs. For example, many aerospace designers working on the JSF (Joint Strike Fighter) project are moving away from their previous reliance on the 'T6' condition of a 7075 aluminium alloy to the 'T73' variant. (Despite all variants of this specification being designated 'obsolescent' by the Metallic Material Data Handbook!).

All of the material properties needed to calculate the static strength of a lug using this material and the ESDU method, are defined in MMDH for the related material specifications L160, L161, L162, EN2127, EN2632, prEN2386, prEN3880 and prEN3881. But there is no commercially available S-N curve for this material despite its popular use in projects such as the JSF! Aerospace materials engineers will judge whether an opportunity beckons here.

Conclusions

This paper presents an anecdotal view of a changing trend in material selection philosophy in advanced engineering projects, gained from the recent experience of ESDU engineers assisting engineers in aerospace and other disciplines. It notes a growing recognition that the 'availability cost' of validated data required for a project can dominate material selection.

A case study shows how this has occurred in the design of lugs but it is undoubtedly relevant to any design problem where advanced material properties such as bearing strength, stress intensity factors and (most of all) an S-N curve are required. It shows why designers and project managers have observed that the time and cost of acquiring such data is of a much greater order than the difference in unit cost between specifying a material that has data and one which doesn't.

Finally, a further observation is made that commercially aware material testing facilities that appreciate this trend will find that an examination of the 'missing' specialised material properties required for advanced (aerospace) design projects may provide valuable market research for deciding where to focus future test programmes.

References

1.	PENNING R.L.	Comparison of design codes with theoretical and test data on lugs. ESDU Memorandum 81, ESDU, London, April 1992 (Available on request).
2.	ESDU	Strength of lugs under axial load. ESDU 91008, ESDU, London, December 1991.
3.	ESDU	Strength of lugs under transverse load. ESDU 06021, ESDU, London, September 2006.
4.	MMPDS-02	Metallic Materials Properties Development and Standardization, MMPDS, (formerly MIL-HDBK-5), Battelle Memorial Institute, Columbus, OH, U.S.A.
5.	ESDU	ESDU 00932, The Metallic Materials Data Handbook. ESDU, London, 2006.
6.	ESDU	Derivation of endurance curves from fatigue test data, including run-outs, ESDU 97024, ESDU, London, June 2003.
7.	DEV-ANAND, N. ROTHWELL, A	Analysis of the transverse rupture of lugs – Investigation of material-specific transverse rupture factors using FEM. ESDU Memorandum No. 152, ESDU, London, July 2005.
8.	MELCON, M.A.	Developments in the analysis of lugs and shear pins. Product Engineering, pp. 160-170, June 1953.
9.	ESDU	Strength of lugs under oblique load, ESDU 08007, London, November 2009

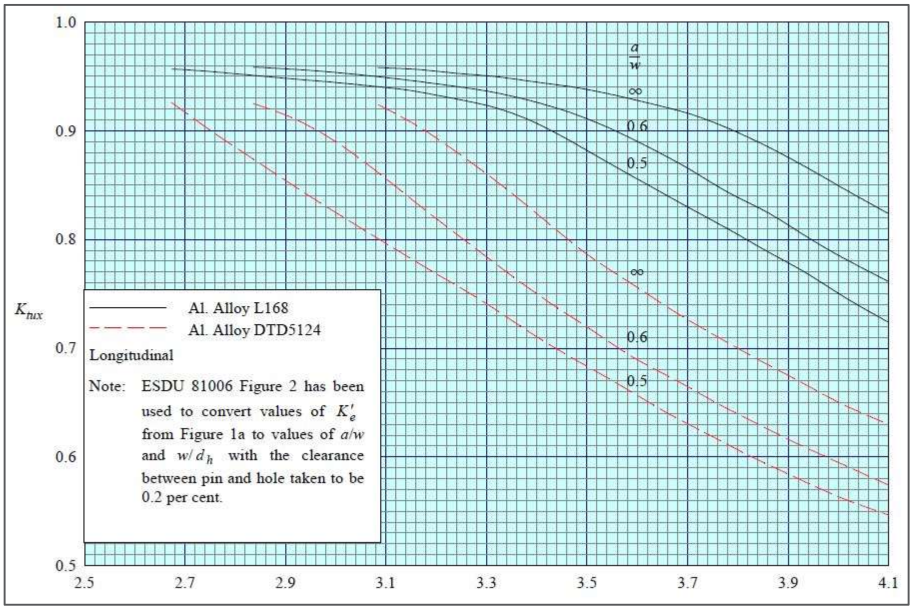
Appendix – Examples from ESDU Data Items 91008 and 06021

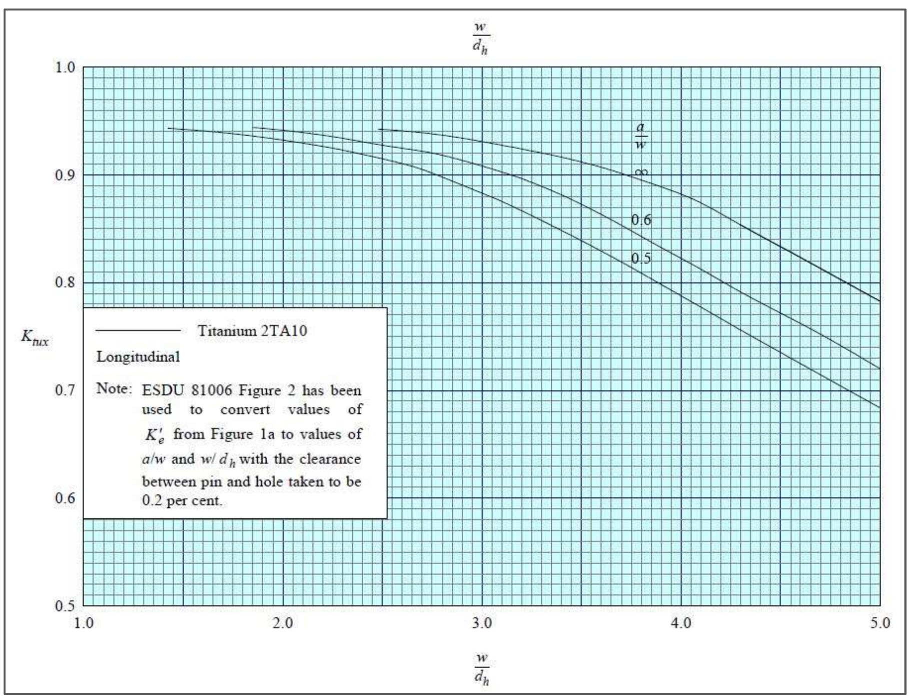
From ESDU 91008:

Figures relating lug geometry parameters to the axial tensile rupture factor used to determine the strength of an axially loaded lug.

These curves show that the tensile rupture factor is dependent upon the material selected and the direction of grain flow.

91008



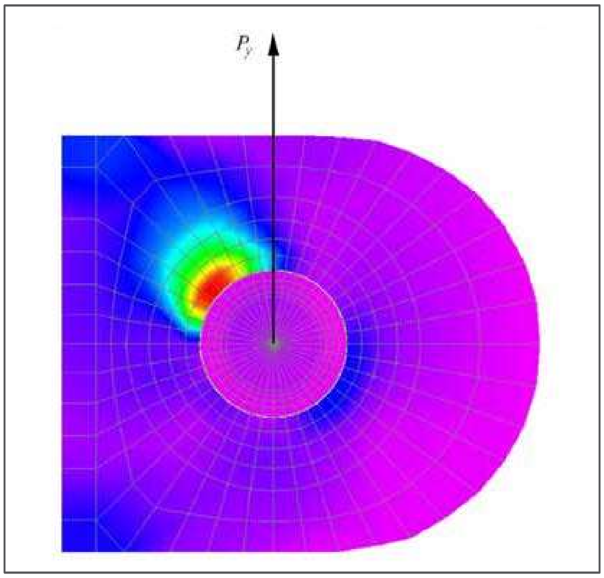


Axial Textile Rupture Factor K_{tux} For parallel-sided Lugs (Round End)

From ESDU 06021:

In References 7 and 8 it is shown that failure of a lug under transverse load is most likely to occur as rupture due to shear and bearing effects in the section of the lug receiving the pin load (see sketch below). These effects are combined in a single empirical expression for the rupture load.

This reflects the material property-dependent nature of the strength analysis required for certification.



Shear strain contour plot of a typical FE lug-pin contact model under transverse loading (undeformed shape)

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