

GUIDE TO THE USE OF THE STRESS AND STRENGTH SUB-SERIES

1. INTRODUCTION

The purpose of this Guide is to help users of Data Items in the Stress and Strength Sub-series to employ them to the best advantage.

The Stress and Strength Sub-series will be very useful in engineering design offices when used correctly. Anyone concerned with stresses and strength would be well advised to make himself familiar with its contents. With practice, and used with intelligence, its range of application will be found to be very wide.

These volumes will be used by engineers who vary considerably in knowledge and experience. Much of this Guide will therefore necessarily be familiar to many readers.

Reference numbers of Data Items that are relevant to the text are given in the margin. Where the text deals with a type of Data Item, the marginal numbers are examples, and not necessarily a complete list of such Items.

2. DERIVATION

The information in the Data Items is believed to be the best available at the time of publication. When preparing a Data Item, ESDU makes a critical assessment of published and available unpublished information, both theoretical and experimental, on the subject. It has many years experience in resolving conflicting views, detecting erroneous information, and in reducing a mass of material to the compact presentation of a Data Item. Through its many contacts, ESDU has access to many unpublished data which are not generally available.

All work is carried out in association with Technical Committees and working parties drawn from industry, research and universities, and including typical users of the Data Items. These Committees and Working Parties, which consist of acknowledged experts in the appropriate fields, guide and monitor the work, and ensure that the results are presented in the form most useful for working design offices.

New information on the subject of existing Data Items is kept under review, and Items are revised when this is considered desirable.

67034 Sometimes it is found that the information available is insufficient, or too uncertain, to provide an authoritative Data Item. In these cases, if data on the subject are required urgently, a "tentative" Data Item is issued, on the principle that a rough guide is preferable to no information. Such Items, labelled "tentative" contain a warning of their limitations.

3. LOCATING THE DATA

Reference to the current ESDU Index will show whether or not there is a Data Item relevant to any particular engineering problem. The Index is a valuable aid to the efficient use of the present volumes and its Introduction should be read carefully as it explains how to make the most effective use of the Index.

If the Data Item required is one of a group it may have an Introductory Item. Such Introductory Items should always be read, as they contain information essential for the effective use of the related group.

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The present volumes contain all those Data Items in the Mechanical Engineering Series that are concerned with stress or strength. They also contain some Data Items from the Aeronautical Sub-series on Fatigue and Structures. These latter have been selected as being of general use in other branches of engineering.

The Data Items of this sub-series are arranged in convenient subject groups and each group is preceded by a guide card giving the group title. Within each group the Data Items are in numerical order. At the front of each volume a fly-leaf is positioned which lists the group titles and the volumes in which they may be found.

Sometimes a reference to the ESDU Index will show that there is a relevant Data Item which is not in this Sub-series. If the volume containing this Data Item is not readily available the individual Data Item may be purchased from ESDU. If desired ESDU can be consulted about the exact contents of the Item before purchase.

Each Data Item contains a description of its scope; if after reading this, any doubts are felt about the application of a Data Item to a particular problem, ESDU should be consulted. It should be noted that ESDU is always ready to help with any kind of difficulty encountered in using its Data Items. ESDU will also be glad to receive suggestions for future Data Items or for improvements and extensions to existing Data Items.

4. MODES OF FAILURE

If too high a stress occurs in a component of a machine or structure, it will fracture, crack or deform to an unacceptable extent. The possibility of failures of the following types should be considered.

4.1 Failure Under a Single Application of Load

4.1.1 Failure in tension

This occurs when the stress reaches the tensile strength of the material. Failure is often considered to have occurred when the stress reaches the yield stress or proof stress of the material. This may be due to an axial tension load, to a bending moment, or to a combination of these.

4.1.2 Failure in shear

This occurs when the shear stress, due either to torsion or to a shear force, reaches the failing shear stress for the material. A thin walled tube in torsion may fail by buckling at a stress less than the failing shear stress of the material. A thin shear web may buckle before failing in shear. (For further details of shear buckling, refer to the Structures Sub-series.)

4.1.3 Failure in compression

This normally produces a buckling failure, and occurs when the applied stress reaches the instability stress for the member. This may be due to an applied axial load in a member, or to an axial load in the compression flange of a beam due to a bending moment, or to a combination of these. Complications arise when a compression member also carries a bending moment. This is dealt with in a general way in a Data Item which serves as an introduction to a group of Data Items on commonly occurring cases of this sort, covering bending moments due to lateral load, eccentricity, and externally applied moments.

It should be noted that members that have an instability stress on elastic theory that is above the proof or yield stress will usually fail by buckling when the stress is in the region of the proof or yield stress, because

of the large reduction in effective Young's modulus. The exceptions to this are short, thick members in compression or bending. In a brittle material these will fail in shear. In a ductile material, an unacceptable amount of permanent deformation is likely to be the criterion of failure.

Although failure in compression is generally due to buckling, buckling in compression does not always imply failure. For example, in a compression member formed by a sheet with attached stiffeners, the sheet may buckle between the stiffeners at a load well below that at which the combination fails. Such buckling is called "stable buckling".

4.1.4 Failure under combined stresses

73004 These may be a combination of tension and/or compression stresses due to loads in different directions, or a combination of shear and tension and/or compression stresses. A common example is a shaft carrying a torque and a bending moment. Text books give about half-a-dozen different ways of dealing with this. A Data Item gives guidance on yielding and failure under combined stresses.

4.2 Brittle Fracture

80036 Brittle fracture is the failure of a material with negligible prior plastic strain. Some materials fail in this way in a uniform, unnotched, section (for example, cast iron and glass). Others, such as steels, which normally fail in a ductile way, can fail in a brittle way in the presence of a sharp notch (for example, a crack) at a value of average tensile stress across the section that is much less than the ultimate tensile strength of the material. Provided gross yielding across the uncracked section of the component does not occur, this failure can be described using the concept of linear elastic fracture mechanics. This analytical method is based on a parameter known as the stress intensity factor, which depends upon the nominal tensile stress on the section and the size of the notch or crack. Failure occurs when the stress intensity factor reaches a critical value, called the fracture toughness, which is a property of the material. A Data Item outlines the principles of linear elastic fracture mechanics.

83023 Fracture toughness is often reduced at high rates of loading. Thus, if impact loads occur, the presence of cracks is likely to be dangerous. Fracture toughness decreases with decrease in temperature. Materials with a high value of fracture toughness all show a sharp drop in value below some critical temperature. It is therefore important to have the value of fracture toughness appropriate to the temperature at which a part will be used.

If fracture toughness is low, a material can fail from a quite small flaw if it is subjected to a high stress (though still well below the tensile strength of the material). The stress involved may be due to an applied load, or may be an internal stress. It should be noted that welding may considerably reduce the fracture toughness of a material local to the region of the weld. Welding may also introduce flaws and internal stresses. An example of these effects is mild steel, which is rarely susceptible to brittle fracture except when welded.

Materials having low fracture toughness should be avoided where possible. If they are used, as they will have to be where a very high strength to weight ratio is essential, great care should be employed in the design and fabrication.

Where high stresses are used in design, it is necessary to confirm that the materials have a fracture toughness that is sufficient to resist growth of the maximum size of flaw at the maximum nominal applied stress. Knowing the fracture toughness of the material, and hence the limiting size of flaw at the nominal design stress, a designer may have to decide the inspection standard required to ensure that flaws do not reach their critical size in service. To do this he needs to know the limiting flaw size and the service loading of the material. It is usual to employ fairly generous factors on the length of the permissible crack.

4.3 Fatigue Failure

- 71027 The possibility of fatigue failure should always be considered when the load in a member fluctuates.
- 75016 Fatigue is the commonest type of failure in machines and in some structures. Data Items are provided that enable a design to be checked for satisfactory fatigue life.
- 69020 Numerical data are provided on the effect of stress-raisers (holes, changes of section *et cetera*). The
- 85045 tensile strength of a part made of ductile material is very little affected by the presence of these stress-raisers, because the resultant stress concentrations are modified when the stress exceeds the elastic limit, and the stress concentrations are reduced to a negligible amount as ultimate failure is approached. The stress concentrations are, however, very important in fatigue failures, where the fatiguing stresses are likely to be in the elastic range. A fatigue calculation that ignored these effects might indicate an unlimited life when in fact the fatigue life was quite short.
- 71009 It is better to eliminate the worst stress-raising features from a design than to spend time calculating their effects on fatigue life. A Data Item gives guidance on design against fatigue, and great advantage will be gained by following this from the beginning of the design stage.
- 75022 Another Data Item describes how calculations may be done to determine whether or not the stresses are less than the fatigue limit.
- 86033 Where necessary, allowance must be made for the effect of corrosion; a corrosive environment may reduce the fatigue strength considerably. This is apart from any effect due to loss of material by corrosion (see Section 4.7.1 below). It is often good practice to provide a protective treatment that prevents a corrosive environment affecting the fatigue life; this is a matter that is likely to be decided by economic considerations. It is necessary to watch that the method of corrosion protection does not itself adversely affect the fatigue life, for example, hydrogen embrittlement during plating may seriously reduce fatigue strength.
- 74027 The fatigue strength of a part is affected by its surface finish. Data are provided that allow this to be taken into account in fatigue calculations.
- 89031 Fatigue cracks usually begin at the surface of a component in a region of high tensile stress. Compressive residual stresses can be induced in these regions by the appropriate surface treatment. Some treatments can be applied to regions of high stress only and these are particularly cost effective for larger components. A Data Item describes the three major treatment groups and their effects on fatigue strength.
- 67012 Fretting also may have an important effect on fatigue strength (see Section 4.7.3 below).
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4.3.1 Fatigue crack propagation

80036 It has been demonstrated that, for most engineering materials (including ductile materials) subjected to
81011 fatigue loading, the stress intensity factor (see Section 4.2) is closely related to the rate of propagation of
85019 the crack. Also, under fatigue loading the crack propagation rate is dependent not only on the crack
length but also on the range of stress in the fatigue cycle and these two parameters can be conveniently
expressed in terms of the stress intensity factor range. Thus, fatigue crack propagation rate data obtained
from simple test specimens and presented in terms of the stress intensity factor range may be employed to
assess the behaviour of components subjected to fatigue loading (in which the existence of cracks or
flaws should not result in catastrophic failure). It is customary to design such that any fatigue cracks that
may develop in a component will be detected before they reduce the strength of the component below an
acceptable level. Design in accordance with such a philosophy generally necessitates prediction of crack
growth, under the load history appropriate to one (or more) inspection intervals, from an initial crack
length. The length of the initial crack is usually taken to be the maximum length that might be missed by
the inspection method to be used. The crack growth prediction is made from the crack propagation rate
data, in order to check that the crack will not grow within the inspection interval to such a length that the
residual strength of the component would be inadequate or, alternatively, to check that the crack growth
rate would not become unacceptably high. If the performance of the component is shown to be
inadequate in either respect it may be necessary to reduce the design stress level in the component, or to
consider shorter inspection intervals in service.

As with brittle failure the crack propagation rate is influenced by environmental conditions and therefore
data relative to the working conditions should be sought.

4.4 Stress-Corrosion Cracking

In some materials the normal rate of corrosion is accelerated by the presence of a stress. In susceptible
materials a sustained stress that is only a small proportion of the tensile strength is enough to have an effect.
When the combination of sustained stress and corrosion leads to cracking, it is called stress-corrosion
cracking. When the sustained stress is high, and the corrosion effects of less importance, it is normally
called stress-cracking.

In steel and aluminium alloys, stress-corrosion cracking occurs only in the stronger aluminium alloys, very
high tensile steels above 1390 MN/m^2 (90 tonsf/in^2) and in stainless steels above 1235 MN/m^2
(80 tonsf/in^2). Even in this range of materials, some are much more susceptible to stress-corrosion than
others. Choice of material is thus important in dealing with this problem.

Some common sources of high sustained tensile stresses can be avoided. High assembly stresses can be
avoided by correct design and manufacture. High stresses due to heat treatment and subsequent machining
can be avoided by the choice of production technique.

4.5 Creep Rupture

Exposure to elevated temperatures results in a reduction of the failing strength of a part. Prolonged loading
at elevated temperatures may result in failure by creep rupture at a stress less than the tensile strength of
the material at the working temperature. The design of such parts should be checked against data obtained
from long-time creep-rupture tests of the material at the appropriate temperature. In materials of limited
ductility (say less than about 5 per cent as determined from creep-rupture tests) the presence of a stress
concentration may reduce the creep-rupture strength, and this should be considered when using test data.

Creep deformations may lead to buckling and subsequent collapse of parts loaded in compression or
bending.

4.6 Deformations

The stresses in a design may be low enough to avoid failure in all the above modes, and yet be high enough to cause unacceptably large deformations. The following types of deformation should be investigated when there is a possibility of their being unacceptable.

4.6.1 Elastic deformation

A part may have an elastic deflection under load that is large enough to interfere with the correct working of a machine. Even if it does not affect correct working, a deflection may look alarming, and frighten customers, and therefore be worthwhile reducing.

4.6.2 Plastic deformation

This occurs when the stress has exceeded the yield stress, and leaves the part with a permanent set. This is often unacceptable. For example, a permanent twist in a shaft will alter the relative positions of the elements attached to it. On the other hand, the effect of local yielding can be beneficial. An example of this is the proof loading of lifting gear. The proof load, by producing yielding at critical points, removes high residual tensile stresses, and also leaves a residual compression stress at points of high tensile stress due to applied loads. Both these effects are beneficial to fatigue life under lower loads.

75022 Where the yielding occurs only very locally, as at the edge of a hole, the overall permanent deformation may be hardly discernible, and therefore permissible. However, in these cases, although the fatigue life under lower loads may well benefit, if the load producing the yielding occurs frequently, the fatigue life of the part is likely to be short.

4.6.3 Creep deformation

In parts liable to creep, the deformation during the maximum required life should be checked against the permissible deformation.

4.7 Additional Considerations

Although the next points are only partly concerned with stress, they should be considered when judging the adequacy of the strength of a part.

4.7.1 Corrosion

The effect of corrosion on stresses is not due merely to the loss of cross-sectional area. Stress concentrations due to corrosion pits can produce drastic reductions of fatigue life, even when the actual loss of material is quite small.

It is generally best to ensure that parts have a corrosion protection appropriate to the environment that they will encounter in service. In the case of important parts, the inspection schedule should ensure that corrosion is discovered and dealt with before it has reached a dangerous extent.

4.7.2 Wear

Whenever two parts have sliding contact, wear must be considered. In the case of intentional sliding contact, this is a matter of having an acceptable bearing stress, in conjunction with the right choice of materials, and a satisfactory method of lubrication.

A type of wear which may indirectly affect strength, by leading to corrosion, is wear of protective coatings; the possibility of this should be considered. For example, a part of a machine that is stood on during routine maintenance operations may need a completely different protective treatment from the rest of the machine.

4.7.3 Fretting

Unintentional rubbing contact may take place between mating members of a nominally rigid joint. This relative movement, which is called fretting, can produce an amount of wear requiring replacement of a part. At the smaller amplitudes it can cause a considerable reduction in fatigue life even when the amount of wear is quite small. A Data Item gives information on the effect of fretting on fatigue strength. It also gives guidance on designing to minimise the effects of fretting.

5. ESTIMATION OF LOADS

In using the Data Items it is generally necessary to know the loads applied to the part under consideration. The accuracy of any answers obtained cannot be better than the accuracy of the applied loads used. Sometimes (for example, in structural steelwork) design loads are prescribed from which a structural analysis will give the loads in members. The accuracy of these loads will depend on the accuracy of the analysis.

In some machines, the upper limit of the loads in members is fixed, for example, by a torque limiting clutch, or a deliberate weak link (shear pin). Another case in which the load is known is where a part is deflected a definite amount, as commonly happens with springs.

In cases where the maximum load is not immediately obvious, it can often be calculated. In a sudden stoppage due to a seized motor or jammed gear box, the loads produced can be calculated from the inertias and stiffnesses of the rest of the machine. The maximum load on lifting gear can be obtained by adding to the dead load the inertia load due to the maximum acceleration or deceleration that it can be given.

Maximum loads may occur under some failure or misuse condition. These need careful consideration. Matters of design philosophy may have to be settled in deciding what types of misuse a machine should be expected to tolerate and under what types of misuse it is entitled to fail.

In the many cases where there is no way of calculating applied loads directly, use should be made of experience based on failures in service. Using a purely nominal value for the applied load, a nominal stress (including, in the case of a fatigue failure, all stress concentration effects) can be calculated at a point of failure. Using the same nominal load, and the same method of stress analysis, a nominal stress can be calculated in parts of a machine which have not failed. This will allow upper and lower limits to be put on the applied loads. It should be noticed that the machines compared here do not need to be of similar detail design – they merely need to work under conditions giving similar applied loads. The base stress used here for comparison with the nominal calculated stress is the yield stress if the failure is a permanent distortion, and the fatigue strength for a fatigue failure. Whether the latter should be the fatigue limit or a higher stress (appropriate to failure at a limited number of loadings) will need considering. By examining the failure or by other methods it may be possible to determine approximately the number of applications of load before failure, and hence obtain an idea of the stress causing the fatigue failure.