Summary

The present HSB sheet provides some basic information about buckling of columns, plates and shells. Further, a nomenclature is given which is used throughout the HSB sheets discussing buckling behaviour.

Key Words: Buckling, column, plate, shell, terms, definitions

References

[1] prEN 1993-1-6: 2005, Eurocode 3: Design of steel structures, Part 1-6: Strength and Stability of Shell Structures.

1 General

In structural design, there should be demonstrated both

- material strength (applying strength conditions) and
- structural strength (applying buckling resistance conditions).

Uncertainties of the design parameters such as material properties, geometry, support conditions and imperfections should be considered.

Under certain loading conditions, a structural system can assume more than one equilibrium state. This phenomenon (known as buckling) is a property of the system as a whole. The condition where the system equilibrium changes is characterized by the buckling resistance. Corresponding values depend on arbitrarily chosen models (e.g. the location at which the buckling stress is determined). For this reason, the buckling stress is not a system property but just a vehicle for its description, which may be useful to predict the system response under operational loading (e.g. to predict a reserve factor).

In case of pure elastic stressing, the system returns into its original equilibrium state after the loads have been reduced. As the elasticity limits have not been exceeded at any location of the system, the structure remains completely intact.

In case of inelastic buckling, the locations of highest stresses are to be checked for inelastic deformation behaviour. These locations are not necessarily those for which the buckling stress has been determined (this may particularly happen if the stress is not uniformly distributed).

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2 Analysis

2.1 Buckling behaviour of columns, plates and shells

The general buckling behaviour of columns, plates and shells is shown in the following sketches. Solid lines give an impression of the real component behaviour whereas dashed lines represent predictions based on suitable models.

2.1.1 Columns

Fig. 1 presents the relation between compressive load and corresponding displacement in the axis of the column.

Characteristic for column buckling is that the predicted critical buckling resistance is a fairly good estimate for the system load carrying capacity.

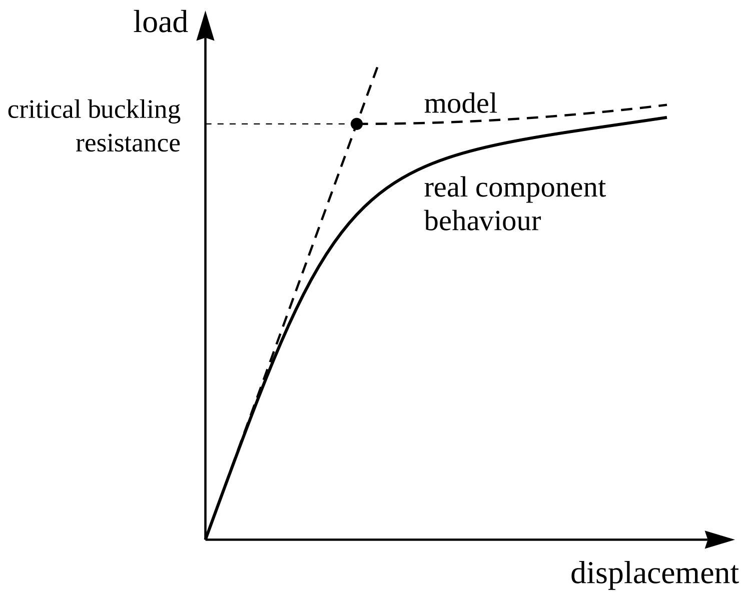

Figure 1: Example for buckling of a column

2.1.2 Plates

Fig. 2 shows the general buckling behaviour of flat (or slightly curved) plates. In the left hand part, the relation between compressive in-plane load and corresponding in-plane displacement is depicted. The right hand part explains the deflection (deformation perpendicular to the plane) under the same load.

For plate buckling, it is to be observed that the system load carrying capacity exceeds the predicted critical buckling resistance.

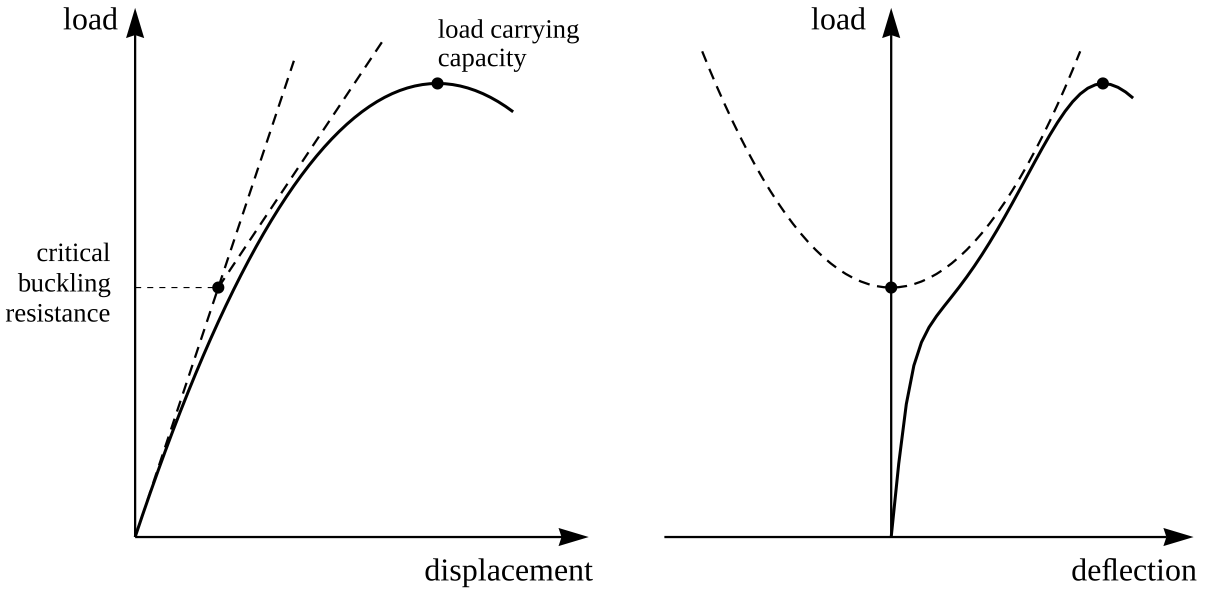

Figure 2: Example for buckling of a plate

2.1.3 Thin-walled isotropic shells

Fig. 3 illustrates in principle the buckling response of a thin-walled isotropic shell. The usual models are able to predict several bifurcation points.

Characteristic is that the load carrying capacity can be lower than the critical buckling resistance, and that it decreases further in the post-buckling regime.

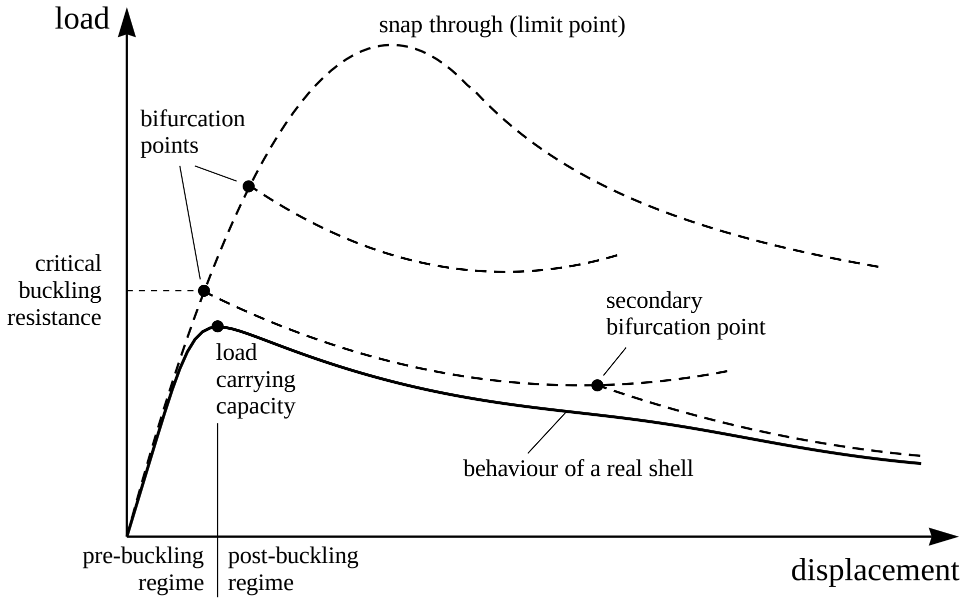

Figure 3: Example for buckling of a general thin-walled isotropic shell

2.1.4 Thin-walled, orthotropically stiffened shells

Fig. 4 depicts the buckling response of an orthotropically stiffened cylindrical shell. The behaviour depends strongly on the stiffness relations of the longitudinal and circumferential stiffeners. The figure is representative for strong circumferential stiffeners and weaker longerons. Typical models are able to predict initial local buckling (usually of the skin), subsequent load re-distribution and overall load carrying capacity.

Similar to plates, the load carrying capacity can significantly exceed the initial local buckling resistance.

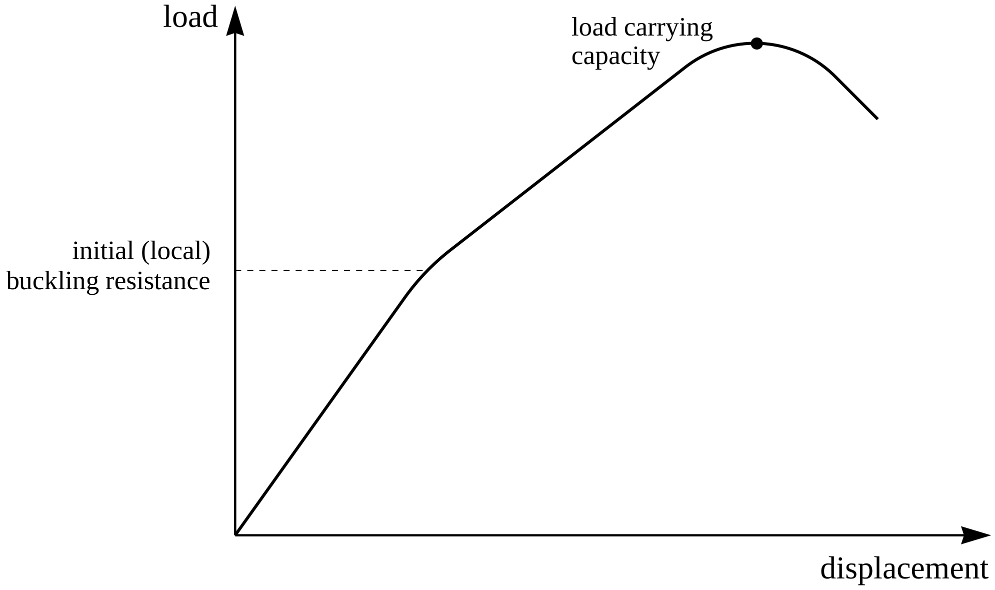

Figure 4: Example for buckling of a thin-walled, orthotropically stiffened cylindrical shell

2.1.5 Thin-walled cylinders under axial compression load

A thin-walled cylinder under axial compression loading is very sensitive to geometrical (and other) imperfections. This becomes obvious, as even the perfect cylinder shows a sudden drop of the carryable load in the post buckling regime. The cylinder behaviour is illustrated in Fig. 5.

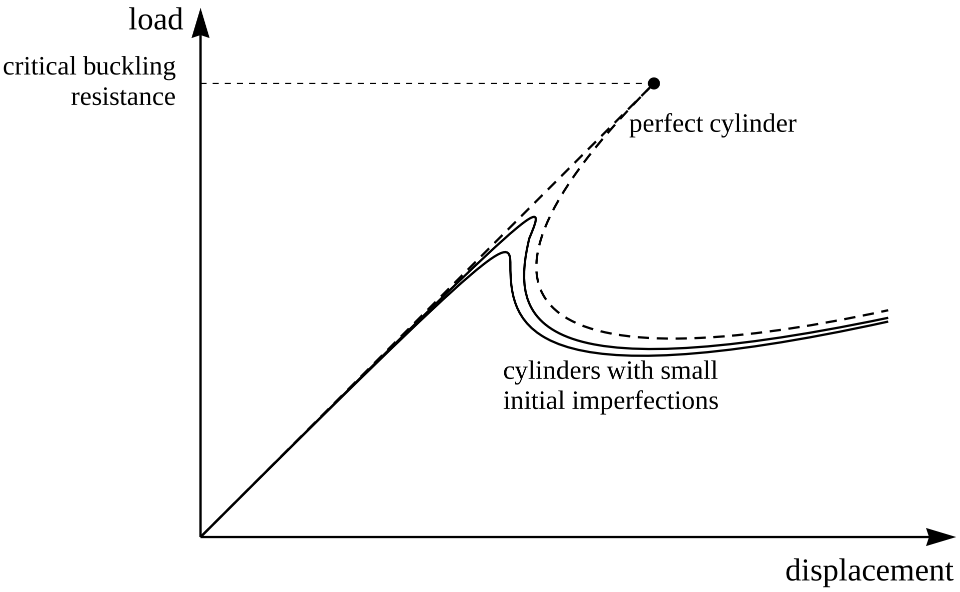

Figure 5: Example for buckling of a thin-walled cylinder under axial compression

2.2 Buckling terms

Buckling

Response of a structural system where more than one state of system equilibrium is possible under the present loading and where the structural system tends to change into the stable equilibrium state.

Note: Buckling leads either to large displacements or to the structure being unable to carry the applied loads.

Comment: A definition - sometimes used elsewhere - 'unstable equilibrium of a structure under loads applied statically or dynamically' can not be accepted, because

- in fact the equilibrium state in the non-buckled mode is the unstable one whereas the equilibrium state in the buckled mode is stable, and
- the equilibrium state does not depend on whether the applied load is static or cyclic; for dynamic loads (i.e. shock and impact loading) the models and theories used contain appropriate additional features.

Comment: Buckling (global as well as local buckling) does not necessarily lead to structural failure. Which type of phenomenon is considered as failure depends on the purpose and intent of a structural design. In some application cases, it is expected that a structure in a local buckling mode is still able to carry operational loads.

Global buckling (also: general buckling)

Buckling mode which affects the structural system as a whole.

Note: Global buckling includes phenomena such as column buckling, plate buckling, shell buckling, lateral buckling of deep beams, snap through buckling.

Local buckling

Buckling mode which affects the structural system only locally.

Note: Local buckling includes phenomena such as crimping (also known as crimpling or crippling), dimpling, wrinkling, intracell buckling, inter rivet buckling.

Bifurcation point

A point in a load-displacement space where two equilibrium paths intersect. Bifurcation buckling is a type of instability which is accompanied with a sudden change of shape of the structure.

Buckling resistance

Resistance of the structure equal to the smallest load under which the structure can respond in more than one system equilibrium state.

Critical buckling resistance

Buckling resistance determined with a model under the prerequisite of idealized conditions.

Note: Such conditions encompass elastic material behaviour, perfect geometry, perfect load application, perfect support, material isotropy (unless idealized non-isotropic material behaviour is included in the model) and absence of residual stresses.

Note: The term critical buckling load (which is the magnitude of the applied load being equal to the critical buckling resistance) may be used instead; however, the term critical buckling resistance should be preferred.

Characteristic buckling resistance

Buckling resistance determined under the prerequisite of possible inelastic material response, geometrical and structural imperfections, follower load effects and residual stresses.

Note: The term characteristic buckling load (which is the magnitude of the applied load being equal to the characteristic buckling resistance) may be used instead; however, the term characteristic buckling resistance should be preferred.

Design buckling resistance

Design value of the buckling resistance taking into account the uncertainties of model-based predictions.

Buckling stress

Key value (see below for details) of a stress field associated with the buckling resistance in the non-buckled equilibrium state.

Note: The buckling stress is utilized to characterize a strength property of a structural system. Thereby, the term buckling stress is used as synonym for buckling strength.

Critical buckling stress

Buckling stress associated with the critical buckling resistance.

Note: The critical buckling resistance is a system property; the stress at a distinct location predicted for the considered state of equilibrium is used as a vehicle to quantify this system property.

Characteristic buckling stress

Buckling stress associated with the characteristic buckling resistance.

Key value of stress

Value of stress in a non-uniform stress field characterizing its magnitude.

Note: It is presumed that the stress field varies proportionally with its key value as scale.

Example: Consider a tapered plate subject to an applied in-plane compressive force acting at the parallel edges which results in different values of the applied stress according to the different local values of the cross section area.

Buckling factor

Factor to obtain the critical buckling resistance of the investigated structural system from a generic problem characterizing quantity.

Note: The buckling factor includes the effects of different support conditions, different cross section properties and non-uniformly distributed applied stresses.

Note: The buckling factor is also applicable for prediction of the critical buckling stress.

Modified buckling factor

Combination of the buckling factor with other factors such as mathematical constants and scaling factors.

Note: The aim of the modified buckling factor is to simplify the utilization of the respective formulas, diagrams and tables.

Modulus reduction factor

Factor conveniently used when converting the critical buckling stress into the characteristic buckling stress in the case that inelastic material response is involved.

Note: The modulus reduction factor is also termed 'plastic reduction factor'.

Buckling factor of safety

Factor of safety used to multiply the limit load (term usual in aircraft design) or the design limit load (term usual in spacecraft design), respectively, to obtain the design buckling load.

Loading

Loads (including normal and shear forces, moments, torques), pressures, temperature and moisture applied to the structural system.

Design buckling load

Limit load (term usual in aircraft design) or the design limit load (term usual in spacecraft design) multiplied by the buckling factor of safety.

Shell (here: thin-walled)

Two-dimensional structure which buckles under loadings causing compressive stresses or shear stresses.

Knock-down factor (KDF)

Reduction factor used to predict the characteristic buckling resistance from the value gained with a model treated under a classic theory.