5.4.1.2 The design factor to be used in a structural stability assessment is based on the type of buckling analysis performed. The following design factors shall be the minimum values for use with shell components when the buckling loads are determined using a numerical solution (i.e., bifurcation buckling analysis or elastic–plastic collapse analysis).

(a) Type 1 – If a bifurcation buckling analysis is performed using an elastic stress analysis without geometric non-linearities in the solution to determine the pre-stress in the component, a minimum design factor of \( \Phi_B = 2 / B_{cr} \) shall be used (see 5.4.1.3). In this analysis, the pre-stress in the component is established based on Design Load Combinations (1) through (9) in Table 5.3.

(b) Type 2 – If a bifurcation buckling analysis is performed using an elastic–plastic stress analysis with the effects of non-linear geometry in the solution to determine the pre-stress in the component, a minimum design factor of \( \Phi_B = 1.667 / \beta_{cr} \) shall be used (see 5.4.1.3). In this analysis, the pre-stress in the component is established based on Design Load Combinations (1) through (9) in Table 5.3.

(c) Type 3 – If a collapse analysis is performed in accordance with 5.2.4, and imperfections are explicitly considered in the analysis model geometry, the design factor is accounted for in the factored load combinations in Table 5.5. It should be noted that a collapse analysis can be performed using elastic or plastic material behavior. If the structure remains elastic when subject to the applied loads, the elastic–plastic material model will provide the required elastic behavior, and the collapse load will be computed based on this behavior.

5.4.1.3 The capacity reduction factors, \( \beta_{cr} \), shown below shall be used unless alternative factors can be developed from published information.

(a) For unstiffened or ring stiffened cylinders and cones under axial compression

\[
\beta_{cr} = 0.207 \quad \text{for} \quad \frac{D_0}{t} \geq 1.247
\]

\[
\beta_{cr} = \frac{338}{389 + \frac{D_0}{t}} \quad \text{for} \quad \frac{D_0}{t} < 1.247
\]

(b) For unstiffened and ring stiffened cylinders and cones under external pressure

\[
\beta_{cr} = 0.80
\]

(c) For spherical shells and spherical, torispherical, elliptical heads under external pressure

\[
\beta_{cr} = 0.124
\]

5.4.2 Numerical Analysis. If a numerical analysis is performed to determine the buckling load for a component, all possible buckling mode shapes shall be considered in determining the minimum buckling load for the component. Care should be taken to ensure that simplification of the model does not result in exclusion of a critical buckling mode shape. For example, when determining the minimum buckling load for a ring-stiffened cylindrical shell, both axisymmetric and non-axisymmetric buckling modes shall be considered in determination of the minimum buckling load.

5.5 PROTECTION AGAINST FAILURE FROM CYCLIC LOADING

5.5.1 OVERVIEW

5.5.1.1 A fatigue evaluation shall be performed if the component is subject to cyclic operation. The evaluation for fatigue is made on the basis of the number of applied cycles of a stress or strain range at a point in the component. The allowable number of cycles should be adequate for the specified number of cycles as given in the User’s Design Specification.

5.5.1.2 Screening criteria are provided in 5.5.2 that can be used to determine if fatigue analysis is required as part of a design. If the component does not satisfy the screening criteria, a fatigue evaluation shall be performed using the techniques in 5.5.3, 5.5.4 or 5.5.5.

5.5.1.3 Fatigue curves are typically presented in two forms: fatigue curves that are based on smooth bar test specimens and fatigue curves that are based on test specimens that include weld details of quality consistent with the fabrication and inspection requirements of this Division.

(a) Smooth bar fatigue curves may be used for components with or without welds. The welded joint curves shall only be used for welded joints.

(b) The smooth bar fatigue curves are applicable up to the maximum number of cycles given on the curves. The welded joint fatigue curves do not exhibit an endurance limit and are acceptable for all cycles.

\( \Phi_B \)

\( \beta_{cr} \)
6.3.3.2 If a specific loading sequence is to be evaluated in accordance with the User's Design Specification, a strain limit damage calculation procedure may be required. This procedure may also be used in lieu of the procedure in paragraph 5.3.3.1. In this procedure, the loading path is divided into \( k \) load increments and the principal stresses, \( \sigma_{1,k}, \sigma_{2,k}, \sigma_{3,k} \), equivalent stress, \( \Delta \sigma_{e,k} \), and change in the equivalent plastic strain from the previous load increment, \( \Delta \varepsilon_{peq,k} \), are calculated for each load increment.

The strain limit for the \( k^{th} \) load increment, \( \varepsilon_{L,k} \), is calculated using Equation (5.8) where \( \varepsilon_{L_u} \), \( m_2 \), and \( \alpha_{sl} \) are determined from Table 5.7. The strain limit damage for each load increment is calculated using Equation (5.9) and the strain limit damage from forming, \( D_{\varepsilon,form} \), is calculated using Equation (5.10). If heat treatment is performed in accordance with Part 6, the strain limit damage from forming is assumed to be zero. The accumulated strain limit damage is calculated using Equation (5.11). The location in the component is acceptable for the specified loading sequence if this equation is satisfied.

\[
e_{L,k} = \varepsilon_{L_u} \cdot \exp \left[ -\left( \frac{\alpha_{sl}}{1 + m_2} \right) \left( \frac{\sigma_{1,k} + \sigma_{2,k} + \sigma_{3,k}}{3 \sigma_{e,k}} \right)^{-1} \right]
\]

\[
D_{\varepsilon,k} = \frac{\Delta \varepsilon_{peq,k}}{\varepsilon_{L,k}}
\]

\[
D_{\varepsilon,form} = \frac{\varepsilon_{cf}}{\varepsilon_{L_u} \cdot \exp \left[ -0.67 \left( \frac{\alpha_{sl}}{1 + m_2} \right)^2 \right]}
\]

\[
D_{\varepsilon} = D_{\varepsilon,form} + \sum_{k=1}^{M} D_{\varepsilon,k} \leq 1.0
\]

5.4 Protection Against Collapse From Buckling

5.4.1 Design Factors

5.4.1.1 In addition to evaluating protection against plastic collapse as defined in paragraph 5.2, a design factor for protection against collapse from buckling shall be satisfied to avoid buckling of components with a compressive stress field under applied design loads.

5.4.1.2 The design factor to be used in a structural stability assessment is based on the type of buckling analysis performed. The following design factors shall be the minimum values for use with shell components when the buckling loads are determined using a numerical solution (i.e. bifurcation buckling analysis or elastic-plastic collapse analysis).

a) Type 1 – If a bifurcation buckling analysis is performed using an elastic stress analysis without geometric non-linearities in the solution to determine the pre-stress in the component, a minimum design factor of \( \Phi_B = 2/\beta_{cr} \) shall be used (see paragraph 5.4.1.3). In this analysis, the pre-stress in the component is established based on the loading combinations in Table 5.3.

b) Type 2 – If a bifurcation buckling analysis is performed using an elastic-plastic stress analysis with the effects of non-linear geometry in the solution to determine the pre-stress in the component, a minimum