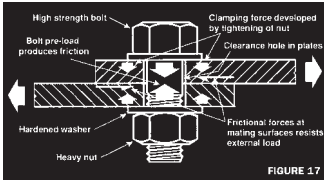


Structural Design Using Blacks Bolts



Acknowledgement: The following summary of design procedures to AS 4100 - 1990 is by Arun Syam and Arthur Firkins of AISC - Technical Services.

The two basic types of metric bolt used in structural engineering in Australia are:

- **commercial bolts to AS 1111 (Strength Grade 4.6)**
- **high strength structural bolts to AS 1252 (Strength Grade 8.8)**

The design provisions for structural bolts are contained in Australian Standard 4100 - 1990: *Steel Structures*. This standard, in limit states design format, superseded AS 1250 - 1981 which was in a working stress format. AS 4100 - 1990 also incorporates the design and installation clauses of high strength bolts from AS 1511 - 1984: *High Strength Bolting Code* - which it also superseded.

Australian Material Standards

The relevant material standards referenced by AS 4100 - 1990 are the current editions:

- AS 1111 ISO metric hexagon precision bolts and screws.

AS 1111 ISO metric hexagon commercial bolts and screws.

AS 1112 ISO metric hexagon nuts, including thin nuts, slotted nuts and castle nuts.

AS 1252 High strength steel bolts with associated nuts and washers for structural engineering.

AS 1275 Metric screw threads for fasteners.

AS 1559 Fasteners - Bolts, nuts and washers for tower construction.

References

Further design guidance is available in the following publications by the **Australian Institute of Steel Construction (AISC)**:

- [1] *Design Capacity Tables for Structural Steel*, 1st Edition, 1991.
- [2] *Bolting of Steel Structures*, 3rd Edition, 1991.
- [3] *Design of Structural Connections*, 4th Edition, 1991.
- [4] *Economical Structural Steelwork*, 3rd Edition, 1991.

Bolting Categories

The strength of bolts is normally specified in terms of the tensile strength of the threaded fastener. As a consequence, grades of bolts are identified in the following manner:

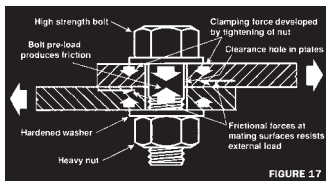


FIGURE 17

Grade X.Y

(eg Grade 4.6 or Grade 8.8)

where

X – is one hundredth of the nominal strength (MPa)

Y – is one tenth of the ratio between nominal yield stress and nominal tensile strength expressed as a percentage.

A standard bolting category identification system has been adopted in AS 4100-1990. These are:

- snug tightened (applies to commercial and high strength structural bolts) designated **4.6/S** and **8.8/s** respectively;
- fully tensioned friction type (high strength structural bolts only) – designated **8.8/TF**;
- fully tensioned, bearing type (high strength structural bolts only) – designated **8.8/TB**;

The system of category designation identifies the bolt being used by using its strength grade designation (4.6 or 8.8) and identifies the installation procedure by a supplementary letter (S–snug; T–full tensioning). For 8.8/T categories, the type of joint is identified by an additional letter (F–friction-type joint; B–bearing joint).

Category **4.6/S** refers to

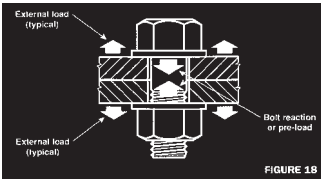
commercial bolts of Strength Grade 4.6 conforming to AS 1111, tightened using a standard wrench to a 'snug-tight' condition.

AS 4100-1990 describes 'snug-tight' as "the tightness attained by a few impacts of an impact wrench or by the full effort of a person using a standard podger spanner". The aim of this installation is to achieve a level of tightness so that all plies in a joint are in full contact. It is a final mode of bolt tightening for 4.6/S and 8.8/S bolting categories, and the first step in full tensioning to 8.8/TF and 8.8/TB bolting categories – see below.

Category **8.8/S** refers to any bolt of Strength Grade 8.8 tightened to a 'snug-tight' condition as described above. These bolts are used as a higher grade commercial bolt to increase the capacity of certain connection types.

Categories **8.8/TF** and **8.8/TB** (or **8.8/T** when referring to both bolt types) refer specifically to high strength structural bolts of Strength Grade 8.8 conforming as AS 1252 *fully tensioned in a controlled manner to the requirements of AS 4100-1990*. The benefit of this bolting category is the increase in performance of the bolted joint in the serviceability limit state (ie limited joint slip), though for a penalty of installed cost – see Refs [2] and [4] above-mentioned. It is recommended that 8.8/TF category be used only in rigid joints where a no-slip joint is essential.

See Table 26 for a summary of the above types and bolting categories.



Modes of Force Transfer

In the design of individual bolts in bolted structural connections, there are three fundamental modes of force transfer to be considered. These are:

- Shear/bearing mode** where the forces are perpendicular to the bolt axis and are transferred by shear and bearing on the bolt and bearing on the connected plies (see Fig 16). Relevant bolting categories are 4.6/S, 8.8/S and 8.8/TB;
- Friction mode**, which is similar to the shear/bearing mode in that forces to be transferred are perpendicular to the bolt axis. However, the transfer of forces does not rely on shear and bearing but is dependant upon the frictional resistance of the mating surfaces (see Fig 17). The relevant bolting category is 8.8/TF;
- Axial tension mode**, when the forces to be transferred are parallel to the bolt axis (see Fig 18). All bolting categories may apply to this.

These modes of force transfer may occur independently or with one another.

Minimum Design Actions on Bolted Connections as AS 4100-1990

Minimum design actions on connections must be considered and these are set out in Clause 9.1.4 of AS 4100-1990. Also, bolts which are required to carry a design tensile force must be proportioned to resist any additional tensile force due to prying action.

Design Procedure to AS 4100-1990

AS 4100-1990 uses the limit states design method in the design, fabrication, erection and modification of steel work in structures. For a description of 'limit states' reference should be made to Ref [1] above. In limit states design the following fundamental inequality must be satisfied.

$$S^* \leq \phi R_u$$

where

S^* = design action effect (ie design shear load and/or design tension load) on the bolt

R_u = nominal capacity of the bolt

ϕ = capacity factor (from Table 28, 29 of AS 4100)

This inequality states the **design action effect (S^*)** must be less than or equal to the **design**

capacity of the bolt (ϕR_u) for the design action considered. The nominal capacity of the bolt is given in AS 4100-1990. It should be noted that the **design action effect (S^*)** is calculated from an acceptable form of analysis using the *factored* limit state load as set out in AS 1170-1989: Minimum Design Loads on Structures (known as the SAA Loading Code).

In bolting design there are three limit states that have to be considered. They are:

- i) strength limit state;
- ii) serviceability limit state;
- iii) fatigue limit state.

STRENGTH LIMIT STATE

In AS 4100-1990 the strength limit state design provisions which apply for static load applications are found in Clause 9.3.2. This applies for all the commonly used bolting categories of 4.6/S, 8.8/S, 8.8/TB and 8.8/TF.

Bolt in Shear – Strength Limit State

The following inequality must be satisfied for a bolt subjected to the design shear force (V_f^*) for strength limit state:

$$V_f^* \leq \phi V_f$$

where

$\phi = 0.8$ (Table 3.4 of AS 4100-1990)

V_f = nominal shear capacity of a bolt

Shear strengths obtained from research have shown that, for bolts in shear, the average shear strength of the bolt was 62% of the tensile strength (f_{uf}). The shear strength of a bolt is directly proportional to the shear area available, this being the core area (A_c) when considering the threaded part of the bolt or the shank area (A_o) when considering the unthreaded part. Therefore, in AS 4100-1990 the nominal shear capacity of a bolt (V_f) is given by:

$$V_f = 0.62f_{uf}k_r(n_n A_c + n_x A_o)$$

where

f_{uf} = minimum tensile strength of the bolt (see Table 26)

k_r = reduction factor to account for the length of a bolted lap connection - L_j (see Table 29). For all other, $k_r=1.0$

n_n = number of shear planes with threads intercepting the shear plane

A_c = minor (core) diameter area of the bolt as defined in AS 1275

n_x = number of shear planes without threads intercepting the shear plane

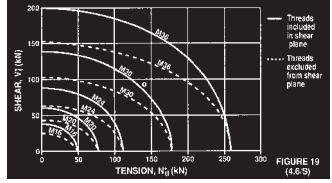
A_o = nominal plain shank area of the bolt

See Table 27 (Grade 4.6) and Table 28 (Grade 8.8) for listings of bolt design shear capacity - strength limit state (ϕV_{fn} and ϕV_{fx}) - for the commonly used structural bolts.

Structural Design Using Blacks Bolts

Note: In Tables 27 and 28 –

$\phi V_{fn} = \phi 0.62 f_{uf} A_c$ for threads included in **single** shear plane, and $\phi V_{fx} = \phi 0.62 f_{uf} A_o$ for threads excluded from **single** shear plane.



Bolt in Tension – Strength Limit State

The following inequality must be satisfied for a bolt subjected to a design tension force (N_{tf}^*) for strength limit state:

$$N_{tf}^* \leq \phi N_{tf}$$

where

$\phi = 0.8$ (Table 3.4 of AS 4100-1990)

N_{tf} = nominal tension capacity of a bolt = $A_s f_{uf}$

and

A_s = tensile stress area of a bolt as specified in AS 1275

f_{uf} = minimum tensile strength of the bolt (see Table 26)

See Table 27 (Grade 4.6) and Table 28 (Grade 8.8) for the listings of bolt design tensions capacity – strength limit state (ϕN_{tf}) – for the commonly used structural bolts.

Bolts that are fully tensioned have, for design purposes, no reduction in nominal tension capacity (see Ref [2] above).

Bolt Subject to Combined Shear and Tension – Strength Limit State

For bolts subject to simultaneous shear and tension forces, tests have shown that the following elliptical interaction relationship applies:

$$(V_f^*/\phi V_f)^2 + (N_{tf}^*/\phi N_{tf})^2 \leq 1.0$$

where V_f^* , V_f , N_{tf}^* , N_{tf} and ϕ are described above.

See Fig 19 (Grade 4.6) and Fig 20 (Grade 8.8) for a plot of the shear tension interaction relationship – strength limit state – for the commonly used structural bolts.

Ply in Bearing – Strength Limit State

Design provisions for a ply loaded by a bolt in bearing are found in Clause 9.3.2.4 of AS 4100-1990. This considers that for a ply subject to a design bearing force (V_b^*) due to a bolt in shear, the following must be satisfied:

$$V_b^* \leq \phi V_b$$

where

$\phi = 0.9$ (Table 3.4 of AS 4100-1990)

V_b = nominal bearing capacity of a ply

V_b is calculated from the *lesser* of:

$$V_b = \text{design bearing capacity due to ply local bearing failure} \\ = 3.2d_f t_p f_{up}$$

and

$$V_b = \text{design bearing capacity due to plate tearout} \\ = a_c t_p f_{up}$$

where

d_f = diameter of the bolt

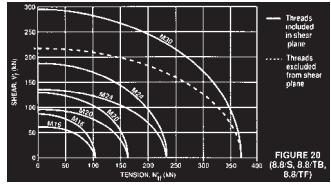
t_p = thickness of the ply

f_{up} = tensile strength of the ply

a_c = minimum distance from the edge of a hole to the edge of a ply, measured in the direct of the component of a force, plus half the bolt diameter. The edge of a ply can include the edge of an adjacent bolt hole.

For Grade 4.6 bolting category, for all reasonable combinations of ply thickness, bolt diameter and end distance, the design capacity for ply in bearing (ϕV_b) exceeds both cases of threads included in and excluded from the shear plane (ie ϕV_f as described above for the bolt in shear – strength limit state).

For the 8.8/S, and 8.8/TB and 8.8/TF bolting categories see Table 28 for listings of ϕV_b for plate tearout and ply local bearing failure. For further details see Ref [1], [2] and [3] above.



Assessment of the Strength of a Bolt Group

Depending on whether loading is in-plane, out-of-plane and also if a couple, shear or both act on the bolt group, Clause 9.4 of AS 4100-1990 should be consulted for the design of actions on individual or critically loaded bolts.

SERVICEABILITY LIMIT STATE

The use of a bolted connection which does not slip or has limited slip under **serviceability** loads may be advisable under certain conditions. This type of connection is known as a friction-type joint and is identified as 8.8/TF bolting category. In AS 4100-1990 the serviceability limit state design provisions are found in Clause 9.3.3. The strength limit state, as mentioned above, should be assessed separately.

Bolt in Shear – Serviceability Limit State

The following inequality must be satisfied for a bolt subjected only to a design shear force (V_{sf}^*) in the

Structural Design Using Blacks Bolts

plane of the interfaces for serviceability limit state:

$$V_{sf}^* \leq \phi V_{sf}$$

where

$\phi = 0.7$ (Clause 3.5.5 of AS 4100-1990)

V_{sf} = nominal shear capacity of bolt, for a friction-type connection

$$= \mu n_{ei} N_{ti} k_h$$

where

μ = slip factor

= 0.35 for clean as-rolled surfaces or determined by testing in accordance with Appendix J of AS 4100-1990

n_{ei} = number of effective interfaces

N_{ti} = minimum bolt tension at installation as specified in Clause 15.2.5.1 of AS 4100-1990 (see Table 30)

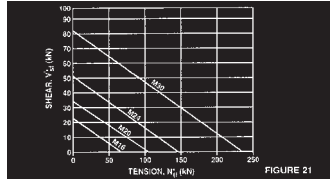
k_h = factor for different hole types as specified in Clause 14.3.5.2 of AS 4100-1990

= 1.0 for standard holes

= 0.85 for short slotted and oversize holes

= 0.70 for long slotted holes

The condition of the faying (or contact) surfaces is of prime importance, *since the slip factor (μ) achieved in practice is directly related to the condition of the faying surfaces.* The slip factor 0.35 given for design purposes in AS 4100-1990 assumes faying surfaces of bare steel to bare steel - ie in the "as-rolled condition".



Often steel members are painted or galvanised and it is important to know what influence this may have on the slip factor. Typical values of the slip factor for various surface preparations are given in Table 31.

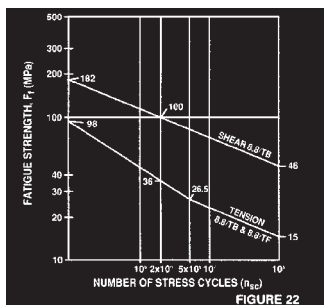
See Table 32 for the listings of bolt design shear capacity - serviceability limit state (ϕV_{sf}) - for the commonly used structural bolts.

Bolt in Tension – Serviceability Limit State

Not relevant in this limit state. Tension loadings for serviceability limit state are only considered when interacting with shear loads at serviceability limit state - see below.

Bolt Subject to Combined Shear and Tension – Serviceability Limit State

For bolts subject simultaneously to shear and tension forces, the following linear interaction relationship applies:


FIGURE 22

$$(V_{sf}^*/\phi V_{sf})^2 + (N_{tf}^*/\phi N_{tf})^2 \leq 1.0$$

where V_{sf}^* , V_{sf} and ϕ are described above. For the tension loads:

N_{tf}^* = design tension force on the bolt

N_{tf} = nominal tension capacity of the bolt

$$= N_{ti}$$

= the minimum bolt tension at installation as specified in Clause 15.2.5.1 of AS 4100-1990 (see Table 30)

See Fig 21 for a plot of the shear tension interaction relationship – serviceability limit state – for the commonly used structural bolts.

FATIGUE LIMIT STATE

It is not possible to review here the fatigue provisions of AS 4100-1990 Section 11. Reference should be made to *AS 4100 Supplement 1-1990: Steel Structures – Commentary*. In summary, a detail category is assigned to bolted connections subject to normal stress (tension) and shear stress. This detail category is a number which

corresponds to the fatigue strength at 2×10^6 cycles on the appropriate S-N curves, a different S-N curve being used for each detail category.

For bolts, AS 4100-1990 provides two detail categories, namely

Detail category 100 bolts in shear, 8.8/TB bolting category where shear stress must be calculated on the core areas, A_c .

Detail category 36 bolts in tension, tensile stress being calculated on the tensile stress area, A_s . Additional tension forces due to prying must be taken into account.

Bolt in Shear – Fatigue Limit State

For shear stress, the uncorrected fatigue strength (f_f) for detail category 100 subject to n_{sc} (number of stress cycles) of loading or stress is given by

$$f_f^2 = (10^5 \times 2 \times 10^6) / n_{sc} \quad \text{when } n_{sc} \leq 10^8$$

This relationship is shown in Fig 22.

For bolts subject to shear force, the fatigue provisions of AS 4100-1990 (Section 11) gives no guidance for 4.6/S and 8.8/S bolting categories. Only 8.8/TF and 8.8/TB are recommended. As no slip occurs with category 8.8/TF, no separate design for fatigue of the bolts is required. AS 4100-1990 does contain design fatigue provisions for 8.8/TB bolting category.

Bolt in Tension – Fatigue Limit State

For normal stress (tension), the uncorrected fatigue strength (f_f) for detail category 36 subject to n_{sc} cycles of loading or stress is given by

$$f_f^5 = (36^3 \times 2 \times 10^6) / n_{sc}$$

when $n_{sc} \leq 5 \times 10^6$

$$f_f^5 = (36^5 \times 10^8) / n_{sc}$$

when $5 \times 10^6 < n_{sc} \leq 10^8$

This relationship is shown in Fig 22.

For bolts subject to tension force, bolting categories 4.6/S and 8.8/S are not recommended and 8.8/TF and 8.8/TB are recommended.

Bolt Subject to Combined Shear and Tension – Fatigue Limit State

AS 4100-1990 does not contain design provisions for these bolts subject to combined shear and tension under fatigue conditions.

The following reference contains a review of research on fatigue in bolted connections: *Guide to Design Criteria for Bolted and Riveted Joints*, Kulak, GL Fisher, JW and Struik, JHA, 2nd Edition, John Wiley 1987.

Design Detail for Bolts

Clause 9.6 of AS 4100-1990 gives the provisions for design details of bolts. This includes minimum pitch, minimum edge distance, maximum pitch, and maximum edge distance. Listings of minimum pitch between centres of fastener holes, and minimum edge distance from the centre of a fastener to the edge of a plate or the flange of rolled section is given in Table 33(a) and 33(b) respectively. Note that minimum edge distance criteria must also be observed from Clause 9.3.2.4 of AS 4100-1990.