A SHORT ACCOUNT OF THE BASIC BEHAVIOUR OF COMMON PRELOADED BOLT JOINTS

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ABSTRACT:

This is a short account of the basic behaviour of common preloaded bolt joints in service, where joint members subject to external loads are clamped by preloaded bolts, and where the latter may be furnished with supplementary bolting members including plain and special washers of any kind and size and bushings that may extend the bolt length even further beyond the combined thickness of the joint members.

The account focuses on tension or tensile joints, also known as joints loaded in tension, under simple conditions where the joint members of a single symmetrical preloaded bolt joint are subject to external loads in the form of pure tension and compression.

In textbooks, these conditions, further simplified by disregarding possible supplementary bolting members, form the basis of the whole understanding of the behaviour of joints, and they are used as the starting point for the description and determination of behaviour in service of the whole range of common preloaded bolt joints.

With this, the account goes beyond the textbooks by extending the conditions dealt with, in connexion with preloaded joints in service, to incorporate possible supplementary bolting members which obviously change the properties and thereby the behaviour of bolt joints.

Based on the account of the fundamental and specific behaviour of common bolt joints, the calculations and illustrations show how it is possible to incorporate supplementary bolting members, and how they change properties and behaviour of bolt joints.

The main conclusion is that it is possible to incorporate supplementary bolting members in a simple consistent way as shown here, and that they may decisively change the behaviour of bolt joints and lead to more efficient use of bolts and thereby to more optimized bolt joints, resulting in greater safety against failure, lower costs, or both.

CONTENTS:

BACKGROUND AND INTRODUCTION:

The following is a short account of the basic behaviour of common preloaded bolt joints in service, where solid joint members subject to external loads are clamped by preloaded bolts, and where the latter may be furnished with supplementary bolting members including different kinds of washers, and bushings that may extend the bolt length even further beyond the total thickness of the joint members.

Special reference has been made to two textbooks dealing with the subject, namely [Bickford 2008] and [Klit 2009].

The account focuses on tension or tensile joints, also known as joints loaded in tension, under the simplest conditions, where the joint members of a single symmetrical preloaded bolt joint are subject to external loads in the form of pure tension and compression, in other words loads that effectively act along the bolt axis, and the description is based on the custom of viewing the joint as having vertical bolt axis and horizontal surfaces of the joint members.

In the textbooks on bolt joints, these conditions form the basis of the whole understanding of the behaviour of joints, and they are used as the starting point for the description and determination of behaviour in service of the whole range of common preloaded bolt joints.

On the other hand, the account goes beyond the textbooks by extending the conditions dealt with, in connexion with preloaded joints in service, to include possible supplementary bolting members which obviously change the properties of the bolt joint to a greater or lesser degree.

Only certain more comprehensive textbooks on bolt joints mention the effects of supplementary bolting members on the joint properties at all, such as [Bickford 2008] section 5.2.4 Stiffness of Bolt-Nut-Washer System, and only without detailed quantification.

In connexion with preloaded joints in service, the textbooks omit possible supplementary bolting members and only deal with the joint members and the bolts themselves, in some cases including nut(s), in other words without possible supplementary bolting members, and this implies the approximation of disregarding the effects on the bolt joint properties by such supplementary bolting members.

For plain plate washers with their very limited thickness, this approximation may be reasonably accurate, depending on the assumptions.

However for other kinds of supplementary bolting members, the change in properties of the bolt joint may make the approximation inaccurate to a significant degree.

At the same time, the actual textbook descriptions of the behaviour of bolt joints in service may appear ambiguous if not misleading when used as the basis for determining how supplementary bolting members fit in and affect the bolt joint properties and behaviour.

One of the main aims of this account is to incorporate supplementary bolting members in a consistent way that gives a realistic presentation of their effects and still leads to conservative values of the bolt loads under service.

The terms and symbols used in this account for some of the relevant bolt joint members and their properties differ from those used in the textbooks, which also differ.

FUNDAMENTAL BEHAVIOUR AND ASSUMPTIONS:

It is crucial to the proper understanding of the behaviour of common bolt joints in service to realize that the bolt and any supplementary bolting members function together as one component whereas the joint members function as the other component.

For the sake of clarity, two new and more general terms are used here for these two fundamental components of the joint, namely the bolting component which includes the bolt and possible supplementary bolting members, and the joint component which includes the joint members.

With this, it is possible to describe and determine the behaviour of common bolt joints in the same way as in the textbooks, only substituting bolting component for bolt and joint component for joint.

And with this, the fundamental behaviour of common bolt joints may be described as follows: the preload is applied to the bolting component which clamps the joint component, and the external loads are applied to the joint component which interacts with the bolting component through their common contact surface at the upper and lower surfaces of the joint members.

For obvious reasons of omission, the textbooks do not expressly confirm this fundamental behaviour, but its validity is evident from the textbook explanation that in general the external loads act within the joint members, as described in [Bickford 2008] section 10.4 Loading Planes and in [Klit 2009] section 6.8 Superposition of pre-load and working loads.

In addition, although indirectly, textbook descriptions of the properties of bolting parts, such as [Bickford 2008] section 5.2.4 Stiffness of Bolt-Nut-Washer System, imply that supplementary bolting members belong to the bolting component.

The main source of ambiguity which may lead to misunderstanding is the classical approach to bolt joint behaviour as described in textbooks, such as [Bickford 2008] section 10.1.3 Joint Diagram for Simple Tensile Loads only to be repeated and then negated in the later section 10.4 Loading Planes, which actually starts by stating the assumption that the external loads act at both ends of the bolt at the inner surfaces of bolt head and nut, rather than at the outer surfaces of the joint, seemingly implying the erroneous conclusion that supplementary bolting members would belong to the joint component rather than the bolting component; [Klit 2009] section 6.8 Superposition of pre-load and working loads is less ambiguous in that the statement of the assumption that the external loads act under the bolt and nut is negated in the first subsection.

Points of action, or loading planes, are used to simplify the determination of bolt joint behaviour through representing the real distribution of the external load over the thickness of each joint member by a concentrated external load at the point of action or loading plane.

While the most realistic determination of bolt joint behaviour is obtained by establishing precise positions of the points of action or internal load planes, this is quite difficult and usually unnecessary, as described in [Bickford 2008] section 10.4 Loading Planes, where the combination of two opposite extreme assumptions are shown to give conservative values of the bolt loads, under varying external loads, as well as of the critical external tensile load where separation of the joint occurs.

The first extreme assumption, common to the textbooks and rephrased here to prevent any ambiguity, is that the points of action or loading planes coincide with the upper and lower surfaces of the joint component, which leads to conservative values of bolt loads.

The second and opposite extreme assumption is that the points of action or loading planes coincide with the joint interface, which leads to a conservative value of the critical external tensile load, quite simply identical to the preload. This forms the basis for requiring a preload at least equalling the maximum external tensile load.

With the simple requirement that the preload must at least equal the maximum external tensile load derived from the second assumption, the description and calculation of bolt joint behaviour in service, including the use of joint diagrams, are generally based upon the first assumption which corresponds to the classical approach to bolt joint behaviour.

The approach used here is based on both assumptions, leading to conservative values of bolt loads under varying external loads, and leading to a conservative value of the critical external tensile load equalling the preload.

An underlying assumption is that the correct preload is adequately established and maintained throughout service life; this subject is not further dealt with here.

It is important to deal with supplementary bolting members in a way that still leads to conservative values of bolt loads under varying external loads and leads to a realistic presentation of their effects.

SPECIFIC BEHAVIOUR AND ASSUMPTIONS:

For each bolt joint component, the properties are determined by the properties of the constituent members, some of which are to be specified.

The crucial property is the relation between load and deflection, as expressed in the term stiffness, represented by the symbol K, and in the inverse term flexibility, also known as spring rate, compliance, or resilience, represented by 1/K.

For a component with a number of members subject to the same load, as is the case both with the bolting component formed by the bolt and possible supplementary bolting members and with the joint component formed by the joint members, the flexibility is additive: the flexibility of the component equals the sum of flexibilities of the members, in other words:

$$1/K = 1/K_1 + 1/K_2 + ... + 1/K_n$$

For two components interacting though common contact surfaces and subject to opposite load variations, as is the case with the bolting component and the joint component of the joint in service where the external loads form load variations superimposed on the preload, the load variations are shared by the components in proportion to their relative stiffnesses.

Using the term K_{BC} for the stiffness of the bolting component and using the term K_{JC} for the stiffness of the joint component, the bolting component is subject to the following share or proportion of the external load variations, termed the load factor, or force ratio, PHI_K:

$$PHI_K = K_{BC}/(K_{BC} + K_{JC}) \qquad \text{Textbook equivalent:} \qquad PHI_K = K_B/(K_B + K_J)$$

Correspondingly, the joint component is subject to the following share or proportion of the load variation:

$$1 - PHI_K = K_{JC}/(K_{BC} + K_{JC}) \qquad \text{Textbook equivalent:} \qquad 1 - PHI_K = K_J/(K_B + K_J)$$

The ratio of the load variation on the bolting component to the load variation on the joint components is:

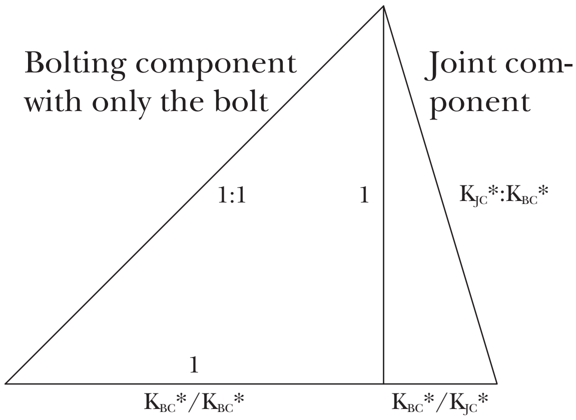
$$PHI_K/1 - PHI_K = K_{BC}/K_{JC} \qquad \text{Textbook equivalent:} \qquad PHI_K/1 - PHI_K = K_B/K_J$$

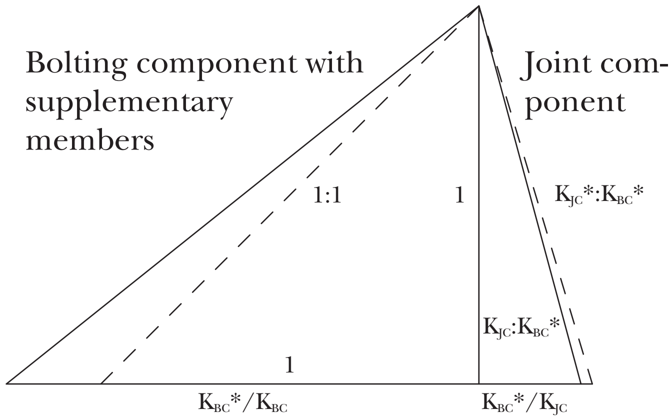
This load variation ratio forms the basis for joint diagrams, also known as deflection diagrams, where loads are shown vertically and deflections are shown horizontally so that the bolting component is represented by a line to the left and the joint component is represented by a line to the right, each with a slope representing the ratio of load to deflection; the two lines cross at a height corresponding to the preload.

Joint diagrams may be drawn to any scale and may be dimensionless.

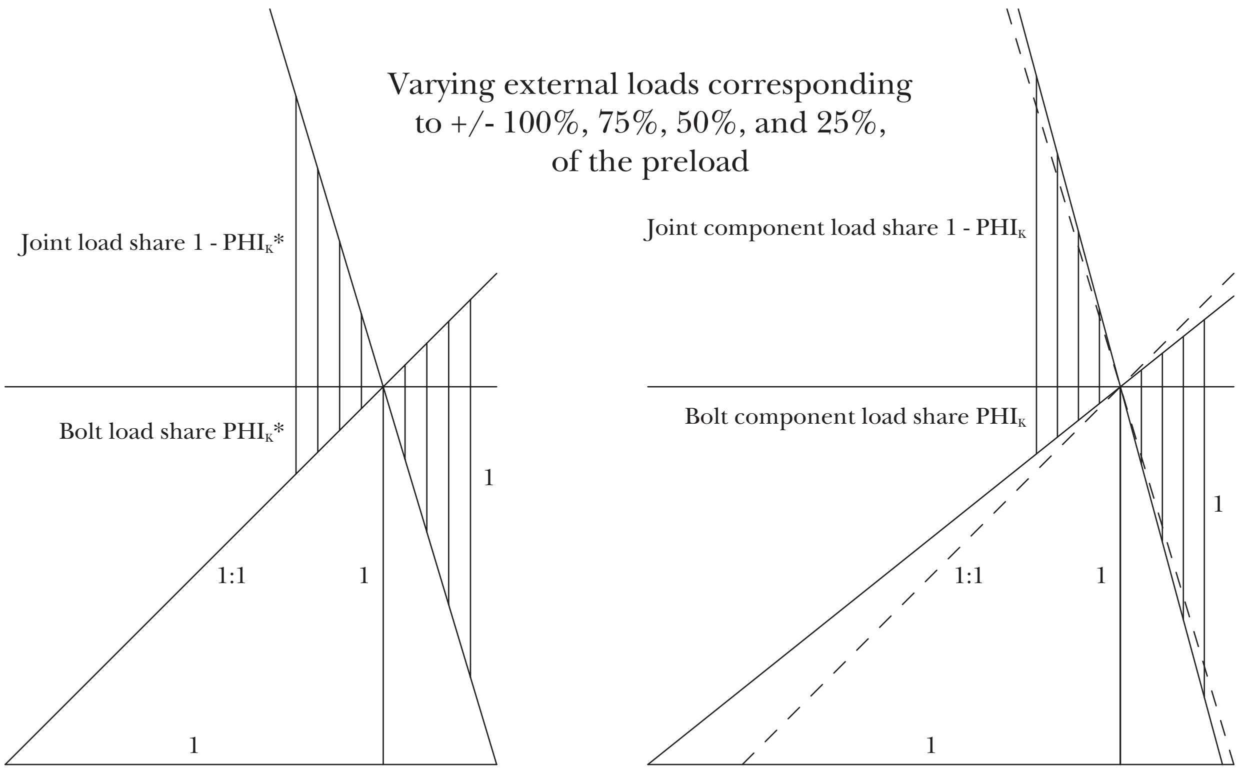
In this account, all joint diagrams are dimensionless and drawn to a scale where a bolting component only consisting of the bolt has a slope of 1:1, to serve as a reference and to facilitate comparisons and presentation of the effects of supplementary bolting members.

Using the term K_{BC}* for the stiffness of a bolting component with only the bolt, and the corresponding term K_{JC}* for the stiffness of the joint component when only clamped by the bolt, the joint diagram under preload may look as follows, for a basic bolt joint with only the bolt and the joint members, and for a bolt joint with supplementary bolting members:





Using the term PHI_K* for the load share of the bolting component with only the bolt, and the corresponding term 1 - PHI_K* for the load share of the joint component when only clamped by the bolt, the joint diagram under varying external loads between +/- 25% and +/- 100% of the preload may look as follows, for a basic bolt joint with only the bolt and the joint members and for a bolt joint with supplementary bolting members:



For any member, and any part of a member, subject to pure tensile or compressive stress under external loads, the stiffness and flexibility can be calculated on the basis of the effective length L or thickness T in the direction of the load, the effective area of the cross section A that the load is applied to, and its Young's modulus E:

$$K = (E*A)/L \qquad \text{or} \qquad K = (E*A)/T$$

$$1/K = L/(E*A) \qquad \text{or} \qquad 1/K = T/(E*A)$$

For an ordinary bolt, different areas apply: the body area A_B applies to the length L_B of the body, and the stress area A_S, which is smaller and depends on the actual thread, applies to the effective length under tensile stress L_S of the threaded part, which is shorter than the actual threaded part. Obviously, the body length must be smaller than the total thickness of all the clamped members, and the total length of the shank must be sufficient.

In order to incorporate the transition areas at either end where the tension in the bolt is transferred to compression in the part of the head/nut that clamps the joint and any supplementary bolting members, end lengths are added to the clamping length of the body/threaded part to represent the transition areas. In this connexion, a member with a threaded hole acts as a nut.

Different textbooks specify different values of the end lengths, such as [Bickford 2008] section 5.1.2 Change in Length of the Bolt, which does not fully incorporate the properties of the nut and the engaged part of the thread as expressly stated in section 5.2.4 Stiffness of Bolt-Nut-Washer System, and [Klit 2009] section 6.7 Deformations in joints due to preload, which does fully incorporate the properties of the nut and the engaged part of the thread, in accordance with the fact that the nut and its engagement with the thread form an integrated part of the bolt in service.

The effective length of the bolt equals the sum of all the relevant lengths.

This means that the bolt as the basic and necessary bolting member can be dealt with in a very simple way, resulting in a single value of stiffness or flexibility.

The bolt has an actual or effective diameter of contact D_B with the nearest clamped member or component corresponding to the lower surface of the head/nut, depending on type of head/nut and possible chamfer.

Any ordinary supplementary bolting member, such as a washer or a bushing, has a thickness, a diameter, an effective area subject to compression, and a diameter of contact with the nearest clamped member or component below which depends on the diameter of contact with the nearest clamping member above and upon the thickness.

The effective area of compression corresponds to an average diameter between the diameters of contact with the nearest clamping member and the nearest clamped member or component.

No textbook specifically deals with the effective area of compression of supplementary bolting members, nor with their diameter of contact. Non specific considerations, such as those in [Bickford 2008] section 5.2.4 Stiffness of Bolt-Nut-Washer System, may lead to exaggerated values of the diameter of contact which may lead to non conservative values of the bolt loads.

Here it is assumed that the effective area of compression may be determined in the same way as for the joint component, only with a nominal thickness twice the actual one corresponding to its being the top half of a symmetrical entity, and that the diameter of contact with the nearest clamped member or component may be determined assuming a simple linear increase in effective area from top to bottom, within the diameter of the component.

This means that the properties of each ordinary supplementary bolting member can be determined in the same way as for each joint member, resulting in a single value of stiffness or flexibility.

Other possible supplementary bolting members may be described in other ways, and their properties may be determined independently in other ways, resulting in a single value of stiffness or flexibility to be specified.

Obviously, the bolting component has a resulting diameter of contact D_{BC} with the joint component which depends on the combination of members and their properties.

For a joint member, the effective area subject to compression A_C, as an average over the thickness of the joint component corresponding to a hollow cylinder, depends upon the clamped thickness of the joint T, which is determined by the clamped thicknesses T_1 and T_2 of the two joint members, and upon the actual or effective diameter D_{JC} of the joint component and the diameter of the hole D_H, and upon the diameter of contact with the bolt component D_{BC}, which is assumed to be identical at the top and bottom of the joint.

Different textbooks specify different ways of determining the value of A_C for joint component members clamped between bolting component members with identical diameters of contact D_{BC}, such as [Bickford 2008] section 5.3.2.1 Stiffness of Concentric Joints, which is only valid within a certain limit to the thickness T of the joint relative to the bolt size, and [Klit 2009] section 6.8 Superposition of pre-load and working loads, which is without such a limit.

In case of different diameters of contact D_{BC}, the lower value is used here, which leads to a conservative value of A_C for joints with different diameters of contact D_{BC}; future versions of this account may be extended to deal with different diameters of contact D_{BC}.

It is assumed here that the same ways of determining the value of A_C can be used for a bolt joint where the lower joint member has a threaded hole and where the upper joint member is clamped against it so it functions as a nut, only using the diameter of contact D_{BC} for the bolt alone and using the clamped thickness T_1 of the upper joint member as the clamped thickness of the joint T, the lower joint member corresponding to a nut; this will lead to a conservative value of A_C, also because the longer engagement length of the thread will make the lower joint member correspond to an oversize nut as shown in [VDI 2230] section 3.1.2 Bild 6 (Figure 6).

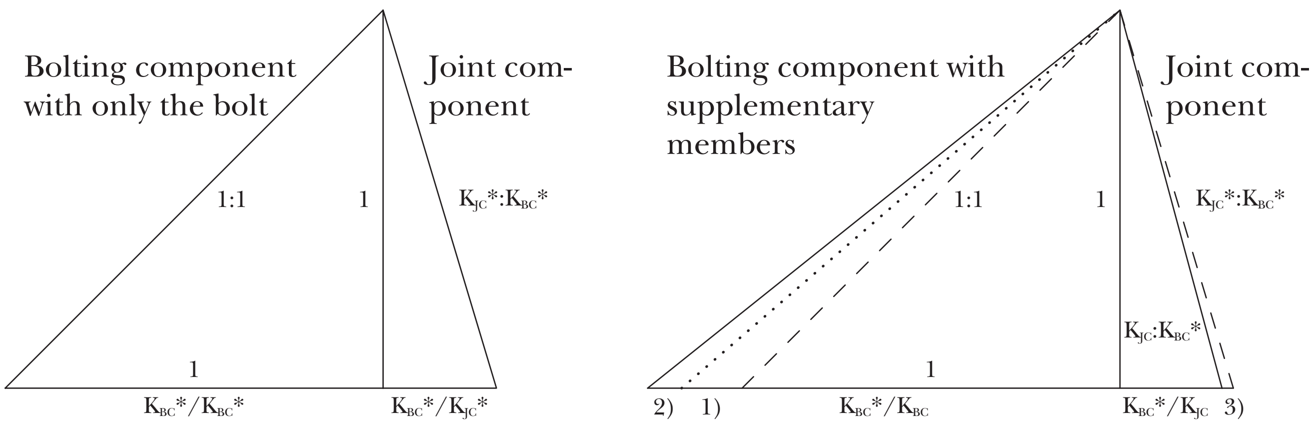
This means that the properties of the joint component can be determined in an unambiguous way, resulting in a single value of stiffness or flexibility.

The incorporation of each supplementary bolting component member will lead to a reduction in the bolt loads through two or three separate non proportional reduction effects:

1) Its thickness will be added to the effective length and thereby the flexibility of the bolt as part of the bolting component;
2) Its own flexibility will be added to the flexibility of the bolting component;
3) Its possibly larger diameter of contact will increase the effective area of the joint members subject to compression and thereby reduce the flexibility of the joint component.

Crucially, the reduction effects 1) and 2) are additive, which means that it is possible to determine the flexibility $1/K_{BC}$ of the joint component from the flexibility $1/K_{BC}$* of the corresponding bolting component with only the bolt by adding 1) the flexibility of the added effective length of the bolt and 2) the flexibility of the added bolting component(s).

This also means that it is possible to add the reduction effects 1) and 2) by directly drawing them into the bolting component side of the joint diagram, as indicated here:



Based upon crucial properties of the different members, a wide variety of bolt joints may be dealt with in a simple and consistent way.

Certain properties have to be specified, such as the possible body length of the bolt, the thicknesses of possible supplementary bolting members, the clamped thickness of the joint component members, and whether the bolt has a head.

Other properties are derived from the specified properties, such as the effective length of the threaded part of the bolt.

Yet other properties are unnecessary for determining the behaviour of the bolt joint, such as the total length of the bolt shank and the total length of its threaded part.

Used as a generic term, the word bolt may represent a number of different threaded fasteners which may clamp the joint in different ways, all defined by a limited number of simple values specified, namely the body length $L_B >= 0$, the head number N_H which is 1 or 0, the nut number N_N which is 0, 1, or 2, and the clamped thickness of the lower joint member $T_2 >= 0$:

- $L_B > 0$, $N_H = 1$, $N_N = 1$, and $T_2 > 0$, define an ordinary bolt clamping both joint members.
- $L_B = 0$, $N_H = 1$, $N_N = 1$, and $T_2 > 0$, define a machine screw clamping both joint members.
- $L_B = 0$, $N_H = 0$, $N_N = 2$, and $T_2 > 0$, define a threaded rod clamping both joint members.
- $L_B > 0$, $N_H = 0$, $N_N = 2$, and $T_2 > 0$, define a stud bolt clamping both joint members.
- $L_B > 0$, $N_H = 1$, $N_N = 0$, and $T_2 = 0$, define an ordinary bolt clamping the upper joint member against the lower joint member which has a threaded hole.
- $L_B = 0$, $N_H = 1$, $N_N = 0$, and $T_2 = 0$, define a machine screw clamping the upper joint member against the lower joint member which has a threaded hole.
- $L_B = 0$, $N_H = 0$, $N_N = 1$, and $T_2 = 0$, define a threaded rod clamping the upper joint member against the lower joint member which has a threaded hole.
- $L_B > 0$, $N_H = 0$, $N_N = 1$, and $T_2 = 0$, define a stud bolt clamping the upper joint member against the lower joint member which has a threaded hole.

In this account, two spreadsheets present the specific properties of constituent members, some of which are to be specified, and the resulting flexibilities and load factors, which form the basis for establishing the behaviour of bolt joints, and also stress range calculations.

Both spreadsheets with explanations are available for download, enabling further calculations as well as a closer examination of the underlying equations, method, and structure.

[Spreadsheet 1] is based upon [Klit 2009] which is based on methods originally laid down by VDI, the Verein Deutscher Ingenieure (Association of German Engineers), in [VDI 2230]. A print is shown in Appendix 2.

In accordance with [Klit 2009], this spreadsheet fully incorporates the properties of the head, the nut, and the engaged part of the thread, and the calculation of the joint component members are not limited to a certain total thickness. It also contains an alternative calculation of joint component stiffness based on an independent source referred to in [Klit 2009] section 6.7 Deformation in joints due to pre-load (reference [5]), for comparison and corroboration.

It should be noted that [Spreadsheet 1] uses the stress area A_S, which represents the average cross section area, for the calculation of the flexibility of the thread, although [Klit 2009] uses a smaller cross section area, termed the root cross section A_3, based upon the inner diameter of the thread, leading to a slightly higher calculated flexibility of the thread. The difference, which only applies to the effective length of the thread, decreases with bolt size; for bolts with sizes from 12 mm and upwards, A_3 is 90% - 94% of A_S.

With this, the use of A_S rather than A_3 is slightly more conservative in terms of bolt loads.

[Spreadsheet 2] is based upon [Bickford 2008]. A print is shown in Appendix 2.

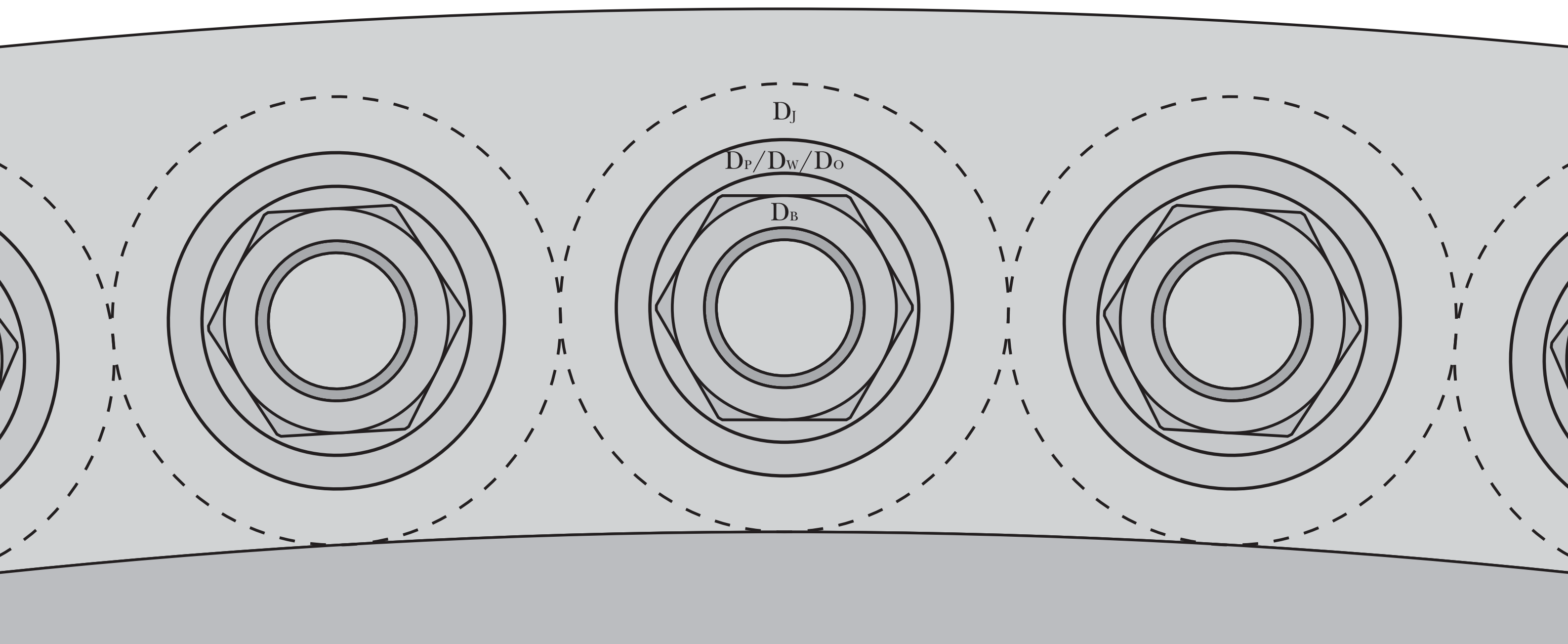
In accordance with [Bickford 2008] this spreadsheet does not fully incorporate the properties of the head, the nut, and the engaged part of the thread, and the calculation of the joint component members is limited to a certain total thickness 8 times the bolt size.

It may be noted that [Spreadsheet 2] also uses the stress area A_S as does [Bickford 2008].

It may be mentioned that the distinct difference in the calculated stiffness of the bolt according to the two spreadsheets is consistent with [SAWA 1976] which forms reference [3] in [Bickford 2008] section 5.2.4 Stiffness of Bolt-Nut-Washer System: as specifically stated in the abstract, which is available for download, the full incorporation of the properties of the head, the nut, and the engaged part of the thread, reduces the stiffness of a 24 mm bolt with a clamping length of 50 mm by 20%.

The considerable difference in the calculated stiffness of the joint members reflects the completely different ways that the effective area subject to compression A_C are calculated.

The following plan shows part of a possible bolt joint which may be represented by the symmetrical joints dealt with in the following calculations and illustrations, indicating the diameters used in the spreadsheets:



CALCULATIONS AND ILLUSTRATIONS:

In the spreadsheets, cells with values to be specified have a grey background, and possible error alerts are shown in red, general error alerts at the bottom.

Possible combinations of basic plate washers, other washers/bushings, and other supplementary bolting members, are to be specified in order to ensure correct values of the diameters of contact and the effective areas subject to compression.

In addition, one or more optional nut extensions, such as a HYTORC Nut, functioning as part of the bolt may be specified; in the calculations, any nut extension forms part of the bolt.

The following pages show diagrams of properties and behaviour in two simple cases with different specific clamping thicknesses of the joint component, without and with supplementary bolting members applied symmetrically at both ends of the bolt, based upon calculations using the two spreadsheets.

Obviously, many other cases, including asymmetric application of supplementary bolting members can be examined.

In both cases a normal 20 mm 8.8 bolt is used, the body length L_B being 10 mm less than its maximum possible length, the joint is preloaded at 80% of the yield strength based on the stress area A_S, and stress ranges in the form of bolt load in % of yield strength as calculated from the stress area A_S at ± full preload as external load.

In the first case, the joint component consists of two members with identical thicknesses $T_1 = T_2 = 25$ mm, their total clamped thickness T being 50 mm. The total thickness of the supplementary bolting members if any, applied symmetrically at either end of the bolt, range from 6 mm to 100 mm, up to twice the clamped thickness of the joint component resulting in a clamping length of the bolt up to thrice the clamped thickness of the joint component. The outer diameter of the supplementary bolting members is either 36 mm or 45 mm.

In the second case, the joint component consists of two members with identical thicknesses $T_1 = T_2 = 75$ mm, their total clamped thickness T being 150 mm. The total thickness of the supplementary bolting members if any, applied symmetrically at either end of the bolt, range from 6 mm to 150 mm, up to the clamped thickness of the joint component resulting in a clamping length of the bolt up to about twice the clamped thickness of the joint component. The outer diameter of the supplementary bolting members is either 36 mm or 45 mm.

The main results of the calculations in the form of a set of tables for each case calculated in each spreadsheet are shown in Appendix 1.

Prints of [Spreadsheet 1] and [Spreadsheet 2] for the first case without supplementary bolting members are shown in Appendix 2.

In the following pages, three new kinds of diagrams, namely flexibility diagrams, relative load factor diagrams, and bolt stress range diagrams, are shown and explained.

All three illustrate the effects of using supplementary bolting members.

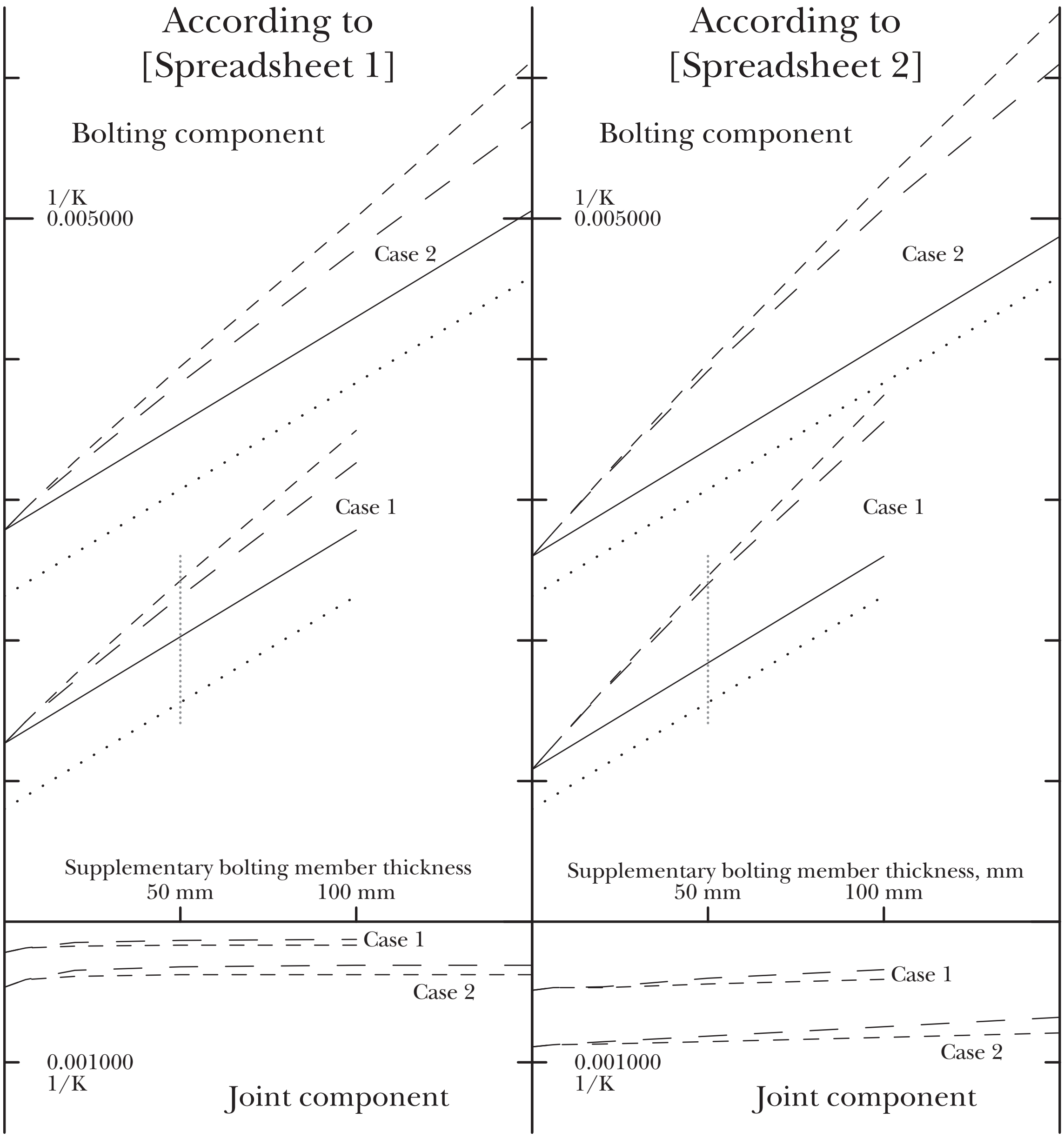
The flexibility diagrams below show flexibilities of members and components for the two cases according to either spreadsheet, as functions of the total thickness of the supplementary bolting members measured in mm, depending on the diameter of the supplementary bolting members.

The clamping length is the sum of the thickness of the joint and the thickness of the supplementary bolting members.

A thickness of 0 corresponds to a bolt alone without supplementary bolting members.

In both cases the thickness of the supplementary members at each end is half their total thickness.

Flexibility diagrams



Component, diameter of supplementary bolting member = 36 mm:

Component, diameter of supplementary bolting member = 45 mm:

Whole bolt by itself:

Clamping part of bolt by itself:

Same thickness of supplementary bolting members and joint:

The following basic properties may be observed:
- The flexibility of the bolt is the sum of the flexibilities of the clamping part which increases linearly with the clamping length, and of the end lengths which is constant;
- The flexibility of the bolting component is the sum of the flexibilities of the bolt, and of the supplementary bolting members which increases non linearly with their total thickness;
- The flexibility of the joint component decreases non linearly with the clamping length.

The non linearity of the flexibilities of the supplementary bolting members and of the joint members, for both cases according to both spreadsheets, is caused by the fact that the effective area subject to compression A_C increases with the thickness at the/each end until it reaches a value equalling the whole area of the cross section.

The different flexibilities of the joint members at different diameters of the supplementary bolting members, for each case according to both spreadsheets, are determined by the different values of the diameter of contact D_{BC}.

Comparing the behaviour in the two cases according to the two spreadsheets, the following may be observed:
- The flexibility of the clamping part of each bolt is the same according to both spreadsheets, consistent with the identity in clamping lengths, and much larger for Case 2, consistent with the much larger clamping lengths;
- The constant flexibility of the end part of the bolt is the same for both cases, but with a distinctly lower value according to [Spreadsheet 2] than according to [Spreadsheet 1] which fully incorporates the properties of the nut and the engaged part of the thread, consistent with the difference in calculation;
- The flexibility of the whole bolt is and much larger for Case 2 than for Case 1, consistent with the combination of one part with a flexibility that increases linearly with the clamping length and one part with constant flexibility, but with a lower value according to [Spreadsheet 2] than according to [Spreadsheet 1], consistent with the difference for the end part;
- For both cases, the flexibility of the supplementary members increases non linearly with their total thickness, consistent with an increasing effective area subject to compression, up to a certain thickness above which the whole cross sectional area becomes subject to compression, with considerably higher value according to [Spreadsheet 2] than according to [Spreadsheet 1] which has higher values of A_C, consistent with the difference in calculation;
- For both cases, the flexibility of the bolting component increases non linearly with their total thickness, with lower values at small thicknesses and higher values at high thicknesses according to [Spreadsheet 2] than according to [Spreadsheet 1], consistent with the differences for the different members;
- For both cases, the flexibility of the joint component decreases non linearly with their total thickness, consistent with an increasing effective area subject to compression, up to a certain thickness above which the whole cross sectional area becomes subject to compression, with considerably higher value according to [Spreadsheet 2] than according to [Spreadsheet 1] which has higher values of A_C, consistent with the difference in calculation.

Further, it may be observed that the flexibility of the supplementary members, if any, is considerably smaller than the flexibility of the whole bolt.

This may also be seen from the deflections in the spreadsheets.

The relative load factor diagrams below show the values of PHI_K/PHI_K^* for each of the two cases according to either spreadsheet.

For each case, the corresponding inverse ratio of bolt length to total thickness of joint component is shown as a dotted line.

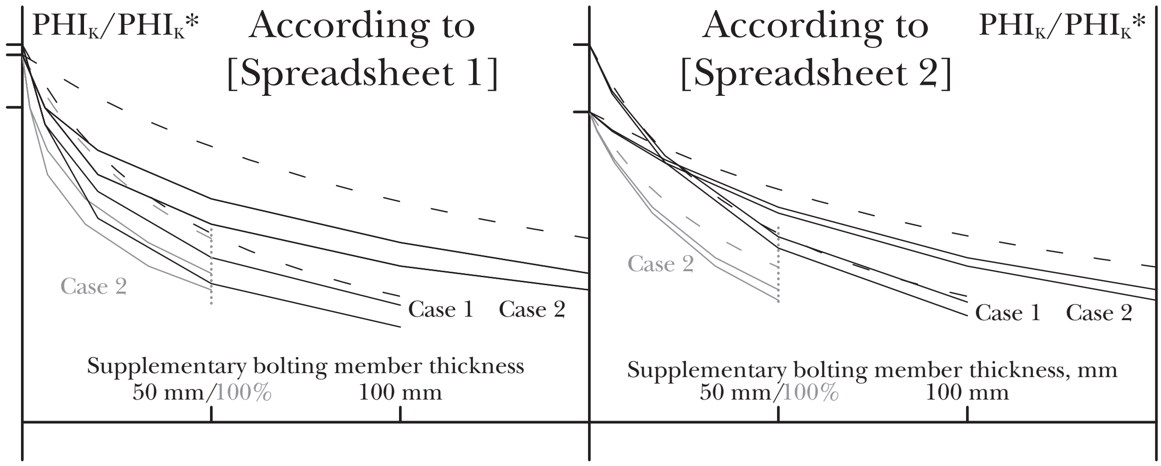
The stress range diagrams below show the stress ranges for each of the two cases according to either spreadsheet.

The stress ranges are in the form of bolt load in % of yield strength as calculated from the stress area A_S, at +/- full preload as external load and a mean value of the full preload which is 80% of the yield strength.

Both sets are shown as functions of the total thickness of the supplementary bolting components, as measured in mm and in % of the total joint thickness respectively.

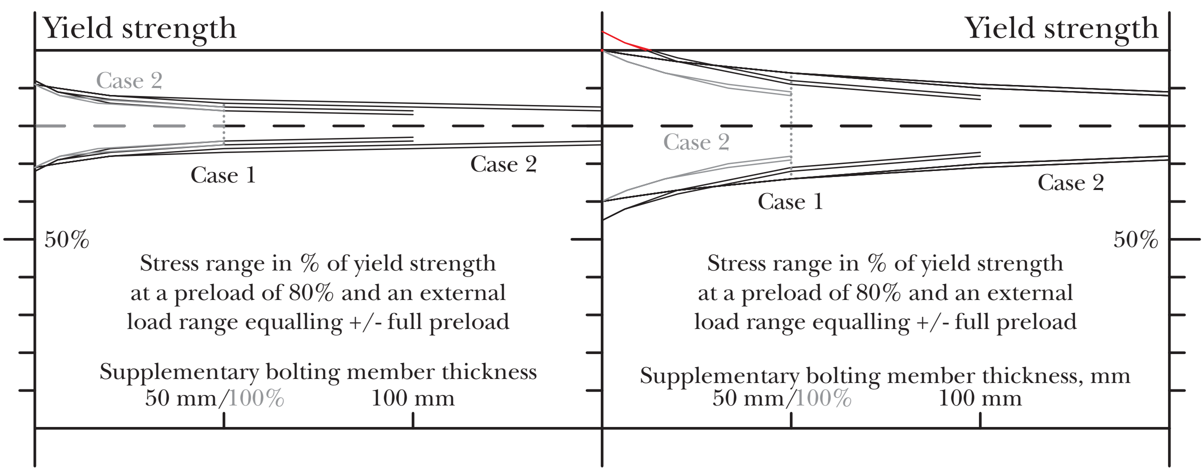
The horizontal scale for % is set to have 100% coinciding with 50 mm.

Relative load factor diagrams



Stress range diagrams

According to [Spreadsheet 1] According to [Spreadsheet 2]



Inverse ratio of bolt length to total thickness of joint component: - - - - - - - - - -
Same thickness of supplementary bolting members and joint: ....

Since the total thickness of the joint component is 50 mm for Case 1, the horizontal scale for % and mm is the same for this case.

Since the total thickness of the joint component is 150 mm for Case 2, the horizontal scale for % is 1:3 of that for mm for this case.

The flexibilities for Case 2 as functions of the thickness in % are shown in grey to discern them from those of Case 1.

The following may be observed:

- For both cases according to both spreadsheets, there is a clear reduction in the load factor and in the stress range with increasing thickness of the supplementary bolting members;
- For both cases, the load factor is lower than the corresponding inverse ratio of bolt length to total thickness of joint component, the difference being greater according to [Spreadsheet 1] than according to [Spreadsheet 2];
- The load factor and the stress range in Case 2 seem high as compared to Case 1 when shown as functions of thickness measured in mm, but when shown as functions of thickness measured in % they are lower than those of Case 1 according to both spreadsheets;
- For both cases, the largest stresses reach or exceed the yield strength according to [Spreadsheet 2] as shown in red, whereas no stresses reach the yield strength according to [Spreadsheet 1].

With this, it is evident that supplementary bolting members reduce the bolt loads under varying external loads by more than the inverse ratio of bolt length to total thickness of joint component.

This means that the inverse ratio of bolt length to total thickness of joint component may be used as a conservative estimate of the reduction factor for the bolt loads under varying external loads that may be obtained with supplementary bolting members.

With this, it is also evident that the bolt loads under varying external loads are considerably higher according to [Spreadsheet 2] than according to [Spreadsheet 1] for all two cases.

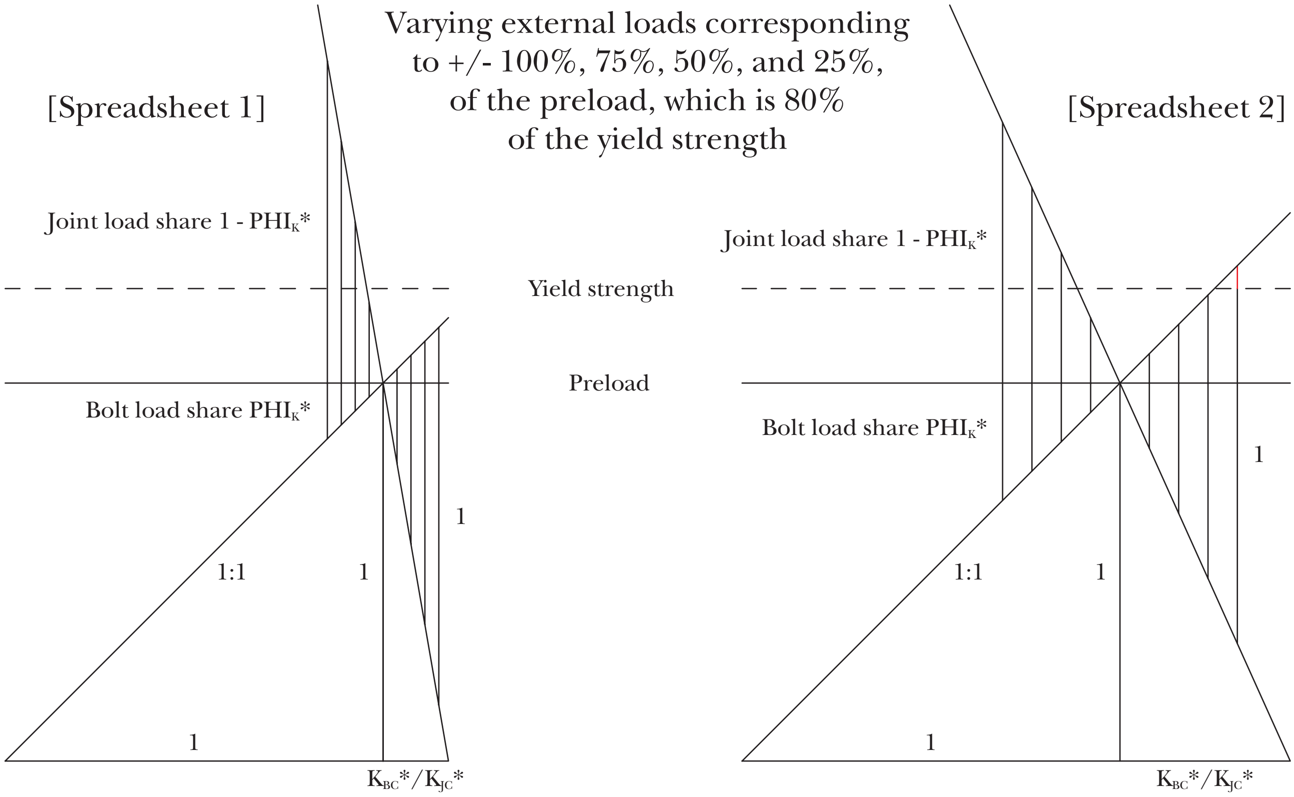
This shows that different ways of calculating the properties will lead to different calculated behaviours of the bolt joint under varying external loads.

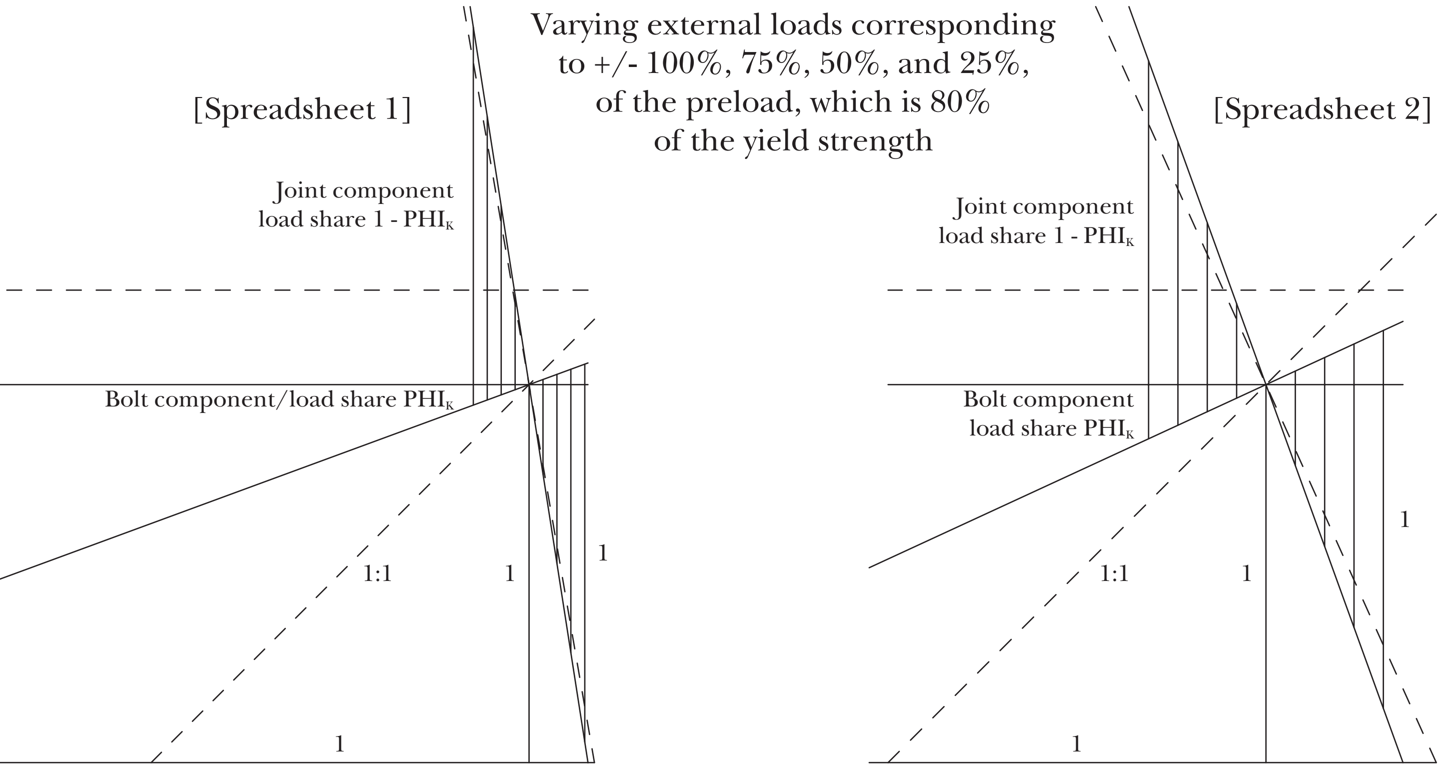
It is also evident that the flexibility diagrams form a consistent basis which makes the behaviour shown in the other diagrams understandable.

The joint diagrams below show Case 1 according to either spreadsheet, with only the bolt, and with supplementary bolting members with 45 mm diameter and 50 mm/100% thickness.

It is evident that the supplementary bolting members reduce the bolt loads under varying external loads very much, and that the bolt loads are considerably lower according to [Spreadsheet 1] than according to [Spreadsheet 2].

It is also evident that the joint diagrams are consistent with the previous diagrams.





CONCLUSIONS:

This account goes beyond the textbooks by extending the conditions dealt with, in connexion with preloaded joints in service, to incorporate possible supplementary bolting members which obviously change the properties and thereby the behaviour of bolt joints.

Based on the account of the fundamental and specific behaviour of common bolt joints, the calculations and illustrations show how it is possible to incorporate supplementary bolting members, and how they change the properties and behaviour of bolt joints, in a consistent way that gives a realistic presentation of their effects and still leads to conservative values of the bolt loads under service.

Based upon crucial properties of the different members, a wide variety of bolt joints may be dealt with in a simple and consistent way.

Two spreadsheets are used: [Spreadsheet 1] is based upon [Klit 2009] which is based on methods originally laid down by VDI, the Verein Deutscher Ingenieure (Association of German Engineers), in [VDI 2230]. [Spreadsheet 2] is based upon [Bickford 2008].

There is a distinct difference in the calculated flexibility of the bolt and a considerable difference in the calculated flexibility of the supplementary bolting members and of the joint members according to the two spreadsheets, consistent with the difference in calculation methods.

Three new kinds of diagrams, namely flexibility diagrams, relative load factor diagrams, and bolt stress range diagrams, are shown and explained, in addition to the well known joint diagrams.

It is evident that supplementary bolting members may reduce the bolt loads under varying external loads very much, and that the bolt loads are considerably lower according to [Spreadsheet 1] than according to [Spreadsheet 2].

It is also evident that the flexibility diagrams form a consistent basis which makes the behaviour shown in the other diagrams understandable.

The main conclusion is that it is possible to incorporate supplementary bolting members in a simple consistent way as shown here, and that they may decisively change the behaviour of bolt joints and lead to more efficient use of bolts and thereby to more optimized bolt joints, resulting in greater safety against failure, lower costs, or both.

REFERENCES:

[Bickford 2008]: Introduction to the Design and Behavior of Bolted Joints, Fourth Edition, Non-Gasketed Joints, by John H. Bickford, 2008

[Klit 2009]: Machine Elements, Analysis and Design, by Peder Klit, Knud Casper & Niels L. Pedersen, 2009

[VDI 2230]: VDI-Richtlinien 2230, Blatt 1: Systematische Berechnung hochbeanspruchter Schraubenverbindungen : Zylindrische Einschraubenverbindungen, Verein Deutscher Ingenieure (VDI-Standard 2230, Part 1: Systematic calculation of high duty bolted joints: Joints with one cylindrical bolt, Association of German Engineers), issued in 1977 and revised in 1986.

A new bilingual German/English edition of VDI 2230 with a much more complex joint flexibility calculation was issued in 2003, replacing the 1986 edition; the same bolt flexibility calculations still apply, apart from a slight reduction in the effective thickness of the lower joint member when it functions as a nut.

Here, as in [Klit 2009], the simpler original calculation method presented in the 1977 and 1986 editions is used.

[SAWA 1976]: On the Deformation of the Bolt Head and Nut in a Bolted Joint, by Toshiyuki SAWA & Kazuo MARUYAMA, 1976. Abstract in English available at www.jstage.jst.go.jp/article/jsme1958/19/128/19_128_203/_article

[Spreadsheet 1]: Metric Spreadsheet to A Short Account of the Basic Behaviour of Common Preloaded Bolt Joints, based upon [Klit 2009], by Jacob Bugge, 2013. Newest edition available at www.bolting.bugge.com

[Spreadsheet 2]: Metric Spreadsheet to A Short Account of the Basic Behaviour of Common Preloaded Bolt Joints, based upon [Bickford 2009], by Jacob Bugge, 2013. Newest edition available at www.bolting.bugge.com

APPENDICES:

Appendix 1: Tables for two cases based upon [Spreadsheet 1] and [Spreadsheet 2]

Appendix 2: A print of [Spreadsheet 1] and a print of [Spreadsheet 2]

APPENDIX 1: TABLES

TABLES BASED ON [SPREADSHEET 1]

Case 1 based upon calculations using [Spreadsheet 1]:
20 mm 8.8 ordinary bolt with different body lengths L_B, in combination with N_P (0 or 2) plate washers with thickness T_P and diameter D_P, and with N_W (0 or 2) washers/bushings with thickness T_W and diameter D_W, with a preload of 80% of the yield strength and external loads up to +/- full preload (+/- 80% of the yield strength)
Both joint members clamped, total clamped thickness 50 mm, effective diameter 60 mm

\Relative stiffnesses Bolting component description	$PHI_K =$ $K_{BC}/(K_{BC}+K_{JC})$	$PHI_K/1 - PHI_K =$ K_{BC}/K_{JC}	$PH_K/$ PHI_K*	Stress range, % of yield strength
$L_B = 40, N_P = 0, N_W = 0$	0.1475	0.1730	1.000	68 - 80 - 92
$L_B = 46, N_P = 2, T_P = 3, D_P = 36, N_W = 0$	0.1164	0.1317	0.789	71 - 80 - 89
$L_B = 46, N_P = 2, T_P = 3, D_P = 45, N_W = 0$	0.1164	0.1317	0.789	71 - 80 - 89
$L_B = 60, N_P = 0, N_W = 2, T_W = 10, D_W = 36$	0.0901	0.0990	0.611	73 - 80 - 87
$L_B = 60, N_P = 0, N_W = 2, T_W = 10, D_W = 45$	0.0797	0.0866	0.540	74 - 80 - 86
$L_B = 90, N_P = 0, N_W = 2, T_W = 25, D_W = 36$	0.0643	0.0688	0.436	75 - 80 - 85
$L_B = 90, N_P = 0, N_W = 2, T_W = 25, D_W = 45$	0.0542	0.0573	0.367	76 - 80 - 84
$L_B = 140, N_P = 0, N_W = 2, T_W = 50, D_W = 36$	0.0457	0.0479	0.310	76 - 80 - 84
$L_B = 140, N_P = 0, N_W = 2, T_W = 50, D_W = 45$	0.0371	0.0386	0.252	77 - 80 - 83

Case 2 based upon calculations using [Spreadsheet 1]:
20 mm 8.8 ordinary bolt with different body lengths L_B, in combination with N_P (0 or 2) plate washers with thickness T_P and diameter D_P, and with N_W (0 or 2) washers/bushings with thickness T_W and diameter D_W, with a preload of 80% of the yield strength and external loads up to +/- full preload (+/- 80% of the yield strength)
Both joint members clamped, total clamped thickness 150 mm, effective diameter 60 mm

\Relative stiffnesses Bolting component description	$PHI_K =$ $K_{BC}/(K_{BC}+K_{JC})$	$PHI_K/1 - PHI_K =$ K_{BC}/K_{JC}	$PH_K/$ PHI_K*	Stress range, % of yield strength
$L_B = 140, N_P = 0, N_W = 0$	0.1435	0.1675	1.000	69 - 80 - 91
$L_B = 146, N_P = 2, T_P = 3, D_P = 36, N_W = 0$	0.1229	0.1401	0.856	70 - 80 - 90
$L_B = 146, N_P = 2, T_P = 3, D_P = 45, N_W = 0$	0.1229	0.1401	0.856	70 - 80 - 90
$L_B = 160, N_P = 0, N_W = 2, T_W = 10, D_W = 36$	0.1062	0.1188	0.740	72 - 80 - 88
$L_B = 160, N_P = 0, N_W = 2, T_W = 10, D_W = 45$	0.0967	0.1070	0.674	72 - 80 - 88
$L_B = 190, N_P = 0, N_W = 2, T_W = 25, D_W = 36$	0.0873	0.0956	0.608	73 - 80 - 87
$L_B = 190, N_P = 0, N_W = 2, T_W = 25, D_W = 45$	0.0773	0.0837	0.539	74 - 80 - 86
$L_B = 240, N_P = 0, N_W = 2, T_W = 50, D_W = 36$	0.0701	0.0773	0.489	74 - 80 - 86
$L_B = 240, N_P = 0, N_W = 2, T_W = 50, D_W = 45$	0.0610	0.0650	0.425	75 - 80 - 85
$L_B = 290, N_P = 0, N_W = 2, T_W = 75, D_W = 36$	0.0581	0.0616	0.405	75 - 80 - 85
$L_B = 290, N_P = 0, N_W = 2, T_W = 75, D_W = 45$	0.0517	0.0545	0.360	76 - 80 - 84

TABLES BASED ON [SPREADSHEET 2]

Case 1 based upon calculations using [Spreadsheet 2]:
20 mm 8.8 ordinary bolt with different body lengths L_B, in combination with N_P (0 or 2) plate washers with thickness T_P and diameter D_P, and with N_W (0 or 2) washers/bushings with thickness T_W and diameter D_W, with a preload of 80% of the yield strength and external loads up to +/- full preload (+/- 80% of the yield strength)
Both joint members clamped, total clamped thickness 50 mm, effective diameter 60 mm

\Relative stiffnesses Bolting component description	$PHI_K = K_{BC}/(K_{BC}+K_{JC})$	$PHI_K/1 - PHI_K = K_{BC}/K_{JC}$	PH_K/PHI_K*	Stress range, % of yield strength
$L_B = 40$, $N_P = 0$, $N_W = 0$	0.3106	0.4506	1.000	55 - 80 - 105
$L_B = 46$, $N_P = 2$, $T_P = 3$, $D_P = 36$, $N_W = 0$	0.2725	0.3745	0.877	58 - 80 - 102
$L_B = 46$, $N_P = 2$, $T_P = 3$, $D_P = 45$, $N_W = 0$	0.2702	0.3703	0.870	58 - 80 - 102
$L_B = 60$, $N_P = 0$, $N_W = 2$, $T_W = 10$, $D_W = 36$	0.2188	0.2800	0.704	62 - 80 - 98
$L_B = 60$, $N_P = 0$, $N_W = 2$, $T_W = 10$, $D_W = 45$	0.2131	0.2708	0.686	63 - 80 - 97
$L_B = 90$, $N_P = 0$, $N_W = 2$, $T_W = 25$, $D_W = 36$	0.1521	0.1794	0.490	68 - 80 - 92
$L_B = 90$, $N_P = 0$, $N_W = 2$, $T_W = 25$, $D_W = 45$	0.1429	0.1667	0.460	69 - 80 - 91
$L_B = 140$, $N_P = 0$, $N_W = 2$, $T_W = 50$, $D_W = 36$	0.0985	0.1092	0.317	72 - 80 - 88
$L_B = 140$, $N_P = 0$, $N_W = 2$, $T_W = 50$, $D_W = 45$	0.0873	0.0956	0.282	73 - 80 - 87

Case 2 based upon calculations using [Spreadsheet 2]:
20 mm 8.8 ordinary bolt with different body lengths L_B, in combination with N_P (0 or 2) plate washers with thickness T_P and diameter D_P, and with N_W (0 or 2) washers/bushings with thickness T_W and diameter D_W, with a preload of 80% of the yield strength and external loads up to +/- full preload (+/- 80% of the yield strength)
Both joint members clamped, total clamped thickness 150 mm, effective diameter 60 mm

\Relative stiffnesses Bolting component description	$PHI_K = K_{BC}/(K_{BC}+K_{JC})$	$PHI_K/1 - PHI_K = K_{BC}/K_{JC}$	PH_K/PHI_K*	Stress range, % of yield strength
$L_B = 140$, $N_P = 0$, $N_W = 0$	0.2552	0.3427	1.000	60 - 80 - 100
$L_B = 146$, $N_P = 2$, $T_P = 3$, $D_P = 36$, $N_W = 0$	0.2403	0.3163	0.942	61 - 80 - 99
$L_B = 146$, $N_P = 2$, $T_P = 3$, $D_P = 45$, $N_W = 0$	0.2394	0.3147	0.938	61 - 80 - 99
$L_B = 160$, $N_P = 0$, $N_W = 2$, $T_W = 10$, $D_W = 36$	0.2156	0.2748	0.844	63 - 80 - 97
$L_B = 160$, $N_P = 0$, $N_W = 2$, $T_W = 10$, $D_W = 45$	0.2131	0.2708	0.835	63 - 80 - 97
$L_B = 190$, $N_P = 0$, $N_W = 2$, $T_W = 25$, $D_W = 36$	0.1765	0.2143	0.692	66 - 80 - 94
$L_B = 190$, $N_P = 0$, $N_W = 2$, $T_W = 25$, $D_W = 45$	0.1719	0.2076	0.674	66 - 80 - 94
$L_B = 240$, $N_P = 0$, $N_W = 2$, $T_W = 50$, $D_W = 36$	0.1351	0.1562	0.529	69 - 80 - 91
$L_B = 240$, $N_P = 0$, $N_W = 2$, $T_W = 50$, $D_W = 45$	0.1282	0.1471	0.502	70 - 80 - 90
$L_B = 290$, $N_P = 0$, $N_W = 2$, $T_W = 75$, $D_W = 36$	0.1089	0.1222	0.427	71 - 80 - 89
$L_B = 290$, $N_P = 0$, $N_W = 2$, $T_W = 75$, $D_W = 45$	0.1002	0.1113	0.393	72 - 80 - 88

METRIC SPREADSHEET TO A SHORT ACCOUNT OF THE BASIC BEHAVIOUR OF COMMON PRELOADED BOLT JOINTS, BASED UPON [KLIT 2009]

By Jacob Bugge MSC, December 2013 Available at www.bolting.bugge.com

Description of bolt:		20	mm	8.8	ordinary bolt	
D, mm	20	D_B, mm	30	D_H, mm	21	360
A_B, mm^2	314	L_B, mm	40		$1/K_B$, mm/kN:	0.000606
A_S, mm^2	245	L_S, mm	To be determined. $1/K_S*1/L_S$, (mm/N)/mm:			0.000019
N_H	1	L_H	10		$1/K_{HN}$, mm/kN:	0.000273
N_N	1	L_N	8	L_T	10	
N_{N+}	0	L_{N+}	10		$1/K_{N+}$, mm/kN:	0.000000
E_B, kN/mm^2	210.000	*Clamping length of bolt, L*:*		*50*	*1/K*:*	*0.000801*
Bolt class	8	8	Yield strength s_Y, N/mm^2		640	
Preload in % of yield strength (A_S)			80	**80**	and in N/mm^2	512
Allowed stress in % of yield strength (A_S)			100		Preload, kN	125.440

Description of supplementary bolting members:	Plate washers:	0	Other member/washer combination numbers		
	Washers/bushings, other:	0	0	0 Total	
	Other members:	0	0	0	0

Plate washer, basic		N_P	0		$1/K_P$, mm/kN:	0.000000
T_P, mm	3	D_P	36	30	A_P, mm^2	453
E_P, kN/mm^2	210.000	Washer/bushing opposite?		NO		30
Washer/bushing		N_W	0		$1/K_W$, mm/kN:	0.000000
T_W, mm	10	D_W	45	30	A_W, mm^2	675
E_W, kN/mm^2	210.000		Total deflection of washers/bushings, mm +/-:			0.000
Other member		N_O	0		$1/K_O$, mm/kN:	0.000000
T_O, mm	50	D_O	50	30	A_O, mm^2	1127
$1/K_O$, mm/kN:	0.000032					
	Plate washer beneath?	NO	Plate washer opposite?	NO		
	Washer/bushing beneath?	NO	Washer/bushing opposite?	NO		
			Deflection of other members, mm +/-:			0.000
Diameter of contact, mm		D_{BC}	30			

Description of joint:		Ordinary joint with two normal members				
Diameter of joint, mm		D_{JC}	60		A_C, mm^2	1086
Joint member 1						
T_1, mm	25				$1/K_1$, mm/kN:	0.000110
E_1, kN/mm^2	210.000					
Joint member 2		*Alternative value of $1/K_{JC}$, only valid for for $D_{JC}>(D_{BC}+T)$:*				*0.000235*
T_2, mm	25				$1/K_2$, mm/kN:	0.000110
E_2, kN/mm^2	210.000					
T, mm	50		50		Joint deflection, mm +/-:	0.023

Calculation of preloaded bolt joint properties:			Bolt deflection, mm +/-:	0.023
Effective shank length, mm: $L_E = L_T+N_{N+}*L_{N+}+N_P*T_P+N_W*T_W+N_O*T_O+T$				60
Effective thread length, mm: $L_S = L_E-L_B$:				20
$1/K_S$, mm/kN: 0.000389	Total bolt flexibility, mm/N: $1/K_B+1/K_S+1/K_{HN}+1/K_{N+}$:			0.001268
Bolting component flexibility, mm/N: $1/K_{BC} = 1/K_B+1/K_S+1/K_{HN}+1/K_P+1/K_W+1/K_O$:				**0.001268**
Joint component flexibility, mm/N: $1/K_{JC} = 1/K_1+1/K_2$:				**0.000219**
Load factor: $PHI_K = K_{BC}/(K_{BC}+K_{JC})$:	**0.1475**		**K_{BC}/K_{JC}:**	**0.1730**
Bolt load range in % of yield strength (A_S) at -/+ full preload:		**68**	**92**	

In the explanations below, values to be specified are shown in **bold**

Bolt size, bolt strength, bolt type

Bolt size, Diameter of contact, Diameter of hole, Area of contact

Area of body, **Length of body (>=0),** Flexibility of body

Stress area of threaded part, Flexibility of thread per mm

Number of heads (0 or 1), Effective thickness of head, Flexibility of head

Number of nuts (0, 1, or 2), Effective thickness of nut; Effective length of engaged part of thread

Number of nut extensions under nut (maybe and/or head), Thickness of nut extension, Flexibility

Young's modulus, *Clamping length of bolt, Flexibility of clamping length for comparison and corroboration*

Bolt class: Ultimate strength in 0.1 kN/mm2 and **Yield strength in 10%,** Yield strength

Preload in % of yield strength (A_s), Final preload in %, Preload as stress

Maximum allowed stress in % of yield strength of threaded part (A_s), Preload

There may be one of either kind of washers and one other member at the/each free end of the bolt

There may be one washer/bushing under the/each plate washer

There may be one plate washer and/or one washer/bushing under the/each other member

Plate washer, basic: **Number** (0, 1, or 2, depending on clamping of joint), Flexibility

Plate washer, basic: **Thickness, Outer diameter,** diameter of contact, Compression area

Young's modulus, **Washer/bushing on opposite side of joint YES/NO,** Diameter of contact

Washer/bushing, other: **Number** (0, 1, or 2, depending on clamping of joint), Flexibility

Thickness, Outer diameter, diameter of contact, Compression area

Washer/bushing, other: Young's modulus, Deflection of washers/bushings, mm +/- at +/- full preload

Other member: **Number** (0, 1, or 2, depending on clamping of joint), Flexibility

Other member: **Thickness, Outer diameter,** diameter of contact, Compression area

Other member: Flexibility

Plate washer beneath other member YES/NO, Plate washer on opposite side of joint YES/NO

Washer/bushing beneath other member YES/NO, Washer/bushing on opposite side of joint YES/NO

Deflection of other members, mm +/- at +/- full preload

Diameter of contact for the bolting component

Either ordinary joint or joint where the lower member has a threaded hole and functions as a nut

Actual or effective diameter of joint, Compression area

Joint member 1: **Clamped thickness,** Flexibility

Joint member 1: **Young's modulus**

Alternative value of joint component flexibility for large values of joint diameters for comparison and corroboration

Joint member 2: **Clamped thickness** (set to 0 if it has a threaded hole), Flexibility

Joint member 2: **Young's modulus**

Total clamped thickness of joint, Total joint deflection, mm +/- at +/- full preload

Total bolt deflection, mm +/- at +/- full preload

Effective shank length including all clamped members and engaged part of thread

Effective thread length

Flexibility of thread, Flexibility of whole bolt including head and nut

Total flexibility of bolting component

Total flexibility of joint component

Load factor and stiffness ratio of bolting component to joint component

Range of bolt loads under service up to -/+ full preload as external load

General error alerts if any

METRIC SPREADSHEET TO A SHORT ACCOUNT OF THE BASIC BEHAVIOUR OF COMMON PRELOADED BOLT JOINTS, BASED UPON [BICKFORD 2008] A2.2.1

By Jacob Bugge MSC, December 2013 Available at www.bolting.bugge.com

Description of bolt:		20	mm	8.8	ordinary bolt		
D, mm	20	D_B, mm	30	D_H, mm		21	360
A_B, mm^2	314	L_B, mm	40		$1/K_B$, mm/kN:		0.000606
A_S, mm^2	245	L_S, mm	To be determined. $1/K_S*1/L_S$, (mm/N)/mm:				0.000019
T_H, mm	13	T_H choice?	0	N_H		1	
T_N, mm	16	T_N choice?	0	N_N		1	1
N_{N+}	0	L_{N+}	10		$1/K_{N+}$, mm/kN:		0.000000
E_B, kN/mm^2	210.000	*Clamping length of bolt, L*:*		*50*		*1/K*:*	*0.000801*
Bolt class	8	8	Yield strength s_Y, N/mm^2			640	
Preload in % of yield strength (A_S)			80	**80**	and in N/mm^2		512
Allowed stress in % of yield strength (A_S)			100		Preload, kN		125.440

Description of		Plate washers:	0	Other member/washer combination numbers			
supplementary		Washers/bushings, other:	0	0		0	Total
bolting members:		Other members:	0	0		0	0
Plate washer plain		N_P	0		$1/K_P$, mm/kN:		0.000000
T_P, mm	3	D_P	36	30	A_P, mm^2		363
E_P, kN/mm^2	210.000	Washer/bushing opposite?		NO			30
Washer/bushing, other		N_W	0		$1/K_W$, mm/kN:		0.000000
T_W, mm	10	D_W	45	30	A_W, mm^2		385
E_W, kN/mm^2	210.000		Total deflection of washers/bushings, mm +/-:				0.000
Other member		N_O	0		$1/K_O$, mm/kN:		0.000000
T_O, mm	3	D_O	36	30	A_O, mm^2		1186
$1/K_O$, mm/kN:	0.000013						
Plate washer beneath?		NO		Plate washer opposite?	NO		
Washer/bushing beneath?		NO		Washer/bushing opposite?	NO		
				Deflection of other members, mm +/-:			0.000
Diameter of contact, mm		D_{BC}	30				

Description of joint:		Ordinary joint with two normal members					
Diameter of joint, mm		D_{JC}	60		A_C, mm^2		488
Joint member 1							
T_1, mm	25				$1/K_1$, mm/kN:		0.000244
E_1, kN/mm^2	210.000						
Joint member 2							
T_2, mm	25				$1/K_2$, mm/kN:		0.000244
E_2, kN/mm^2	210.000						
T, mm	50		50	Joint deflection, mm +/-:			0.042

Calculation of preloaded bolt joint properties:		Bolt deflection, mm +/-:	0.042
Effective bolt length, mm: $L_E = (N_H*T_H+N_N*T_N)/2+N_{N+}*T_{N+}+N_P*T_P+N_W*T_W+T_1+T_2$:			64.5
Effective thread length, mm: $L_S = L_E-L_B$:			24.5
$1/K_S$, mm/kN:	0.000476	Total bolt flexibility, mm/N: $1/K_B+1/K_S+1/K_{HN}+1/K_{N+}$:	0.001082
Bolting component flexibility, mm/N: $1/K_{BC} = 1/K_B+1/K_S+1/K_P+1/K_W+1/K_O$:			**0.001082**
Joint component flexibility, mm/N: $1/K_{JC} = 1/K_1+1/K_2$:			**0.000488**
Load factor: $PHI_K = K_{BC}/(K_{BC}+K_{JC})$:	**0.3106**	**K_{BC}/K_{JC}:**	**0.4506**
Bolt load range in % of yield strength (A_S) at -/+ full preload:	**55**		**105**
		REDUCE PRELOAD/EXTERNAL LOAD	

In the explanations below, values to be specified are shown in **bold**

Bolt size, bolt strength, bolt type

Bolt size, Diameter of contact, Diameter of hole, Area of contact

Area of body, **Length of body (>=0),** Flexibility of body

Stress area of threaded part, Flexibility of thread per mm

Default thickness of head, **Other thickness of head if not default, Number of heads (0 or 1)**

Default thickness of nut, **Other thickness of nut if not default,** Actual/effective number of nuts

Number of nut extensions under nut (maybe and/or head), Thickness of nut extension, Flexibility

Young's modulus, *Clamping length of bolt, Flexibility of clamping length for comparison and corroboration*

Bolt class: Ultimate strength in 0.1 kN/mm2 and **Yield strength in 10%,** Yield strength

Preload in % of yield strength (A_s), Final preload in %, Preload as stress

Maximum allowed stress in % of yield strength of threaded part (A_s), Preload

There may be one of either kind of washers and one other member at the/each free end of the bolt
There may be one washer/bushing under the/each plate washer
There may be one plate washer and/or one washer/bushing under the/each other member

Plate washer, basic: **Number** (0, 1, or 2, depending on clamping of joint), Flexibility

Plate washer, basic: **Thickness, Outer diameter,** diameter of contact, Compression area

Young's modulus, **Washer/bushing on opposite side of joint YES/NO,** Diameter of contact

Washer/bushing, other: **Number** (0, 1, or 2, depending on clamping of joint), Flexibility

Washer/bushing, other: **Thickness, Outer diameter,** diameter of contact, Compression area

Washer/bushing, other: Young's modulus, Deflection of washers/bushings, mm +/- at +/- full preload

Other member: **Number** (0, 1, or 2, depending on clamping of joint), Flexibility

Other member: **Thickness, Outer diameter,** diameter of contact, Compression area

Other member: Flexibility

Plate washer beneath other member YES/NO, Plate washer on opposite side of joint YES/NO
Washer/bushing beneath other member YES/NO, Washer/bushing on opposite side of joint YES/NO
Deflection of other members, mm +/- at +/- full preload

Diameter of contact for the bolting component

Either ordinary joint or joint where the lower member has a threaded hole and functions as a nut

Actual or effective diameter of joint, Compression area

Joint member 1: **Clamped thickness,** Flexibility

Joint member 1: **Young's modulus**

Joint member 2: **Clamped thickness** (set to 0 if it has a threaded hole), Flexibility

Joint member 2: **Young's modulus**
Total clamped thickness of joint, Total joint deflection, mm +/- at +/- full preload

Total bolt deflection, mm +/- at +/- full preload

Effective bolt length including all clamped members and addition at head and nut

Effective thread length

Flexibility of thread, Flexibility of whole bolt

Total flexibility of bolting component

Total flexibility of joint component

Load factor and stiffness ratio of bolting component to joint component

Range of bolt loads under service up to -/+ full preload as external load
General error alerts if any