Investigates the resistance of blind bolts featuring headed anchors when subjected to both tension and shear loads simultaneously

By

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ABSTRACT

It is generally accepted that the application of tubular steel profiles as columns in steel construction is attractive, from a structural and architectural point of view. Their use, however, is hindered due to the lack of access which does not allow for standard bolted connections to be utilised. Consequently, so-called blind-bolts have been developed over the years to overcome this issue, allowing bolted connections to be formed when access as such is limited. The design of structural joints using the commercially available blind-bolts is currently restricted to simple construction (non-moment resisting).

More recently, a modified blind-bolt, named the Extended Hollo-bolt, has been developed at the University of Nottingham to extend the application of the technique to moment-resisting construction. Following a review of the existing information, it is established that the present data does not permit the design of the proposed technology. That is because of a lack of knowledge in its behaviour under combined tension and shear forces.

This study investigates the resistance of the Extended Hollo-bolt when it is subjected to various ratios of combined tension and shear forces. An original test rig was designed and manufactured in order to apply simultaneous, monotonic tension and shear forces on the bolt.

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$F_{v,Rd}$ is the design shear resistance per bolt

$F_{t,Rd}$ is the design tension resistance per bolt

$S_{j,int.}$ is the initial rotation stiffness

$F_{v,Ed}$ is the design shear force on the bolt

$F_{t,Ed}$ is the design tension force on the bolt

F_t is the tension force on the bolt

F_s is the shear force on the bolt

P_t is the tension capacity of the bolt

P_s is the shear capacity of the bolt

$S_{j,int.}$ is the initial rotation stiffness

$S_{j,int.}$ is the initial rotation stiffness

K_b is related to the bracing system in the building k_b: 8 for braced frame

k_b: 25 for un-braced frame

I_b is the second moment of area of a beam

L_b is the length of a beam (centre to centre)

E is the modulus of elasticity of steel

d_n is the nominal bolt diameter

d_k is the core diameter of bolt

F_{ts} is the strength function for a bolt in tension

F_{td} is the design strength for a bolt in tension

f_{ub} is the ultimate tensile strength of the bolt material

A_s is the area of threaded portion

γ_m is the partial safety factor

F_{vs} is the strength function for a bolt in shear

F_{vd} is the design strength for a bolt in shear

f_{ub} is the ultimate tensile strength of the bolt material

A is the cross – section of the shank of the bolt

γ_m is the partial safety factor

σ is the normal stress

τ is the shear stress

$\sigma_{max.}$ is the maximum normal stress

$\tau_{max.}$ is the maximum shear stress

R_s stands for shear load ratio

R_t stands for tension load ratio

F_t , F_v are the tension and shear componets in the bolt respectively

F_{td} , F_{vd} are the design strength for a bolt under pure tension and pure shear respectively

$r_{e,tension}$: tension component from experimental result.

$r_{tm,tension}$: theoritical tension resistance of the bolt obtained by strength function.

$r_{e,shear}$: shear component from experimental result.

$r_{tm,shear}$: theoritical shear resistance of the bolt obtained by strength function

F_{id} is the Design strenght of bolt under combined tension and shear

F is the applied load through the Instron machine

F_t is the tension component that calculated as R . cos Ø in this research

F_v is the shear component which is calculated as R . sin Ø in this research

LIST OF ABBREVIATIONS

EHB Extended Hollobolt

HB Hollobolt

RHS Rectangular Hollow Section

RMH Reverse Mechanism Hollobolt

EC3 Eurocode Design Code 3

DIN Deutsches Institute fur Normung (German Institute for Standardisation)

BS British Standard

SHS Structural Hollow Section

CEN European Committee for Standardisation

1 INTRODUCTION

Structural steel sections are available in two shapes: open and hollow section. Over the years, structural hollow sections (SHS) have experienced a significant growth in the field of steel structures because of their flexibility which has opened up exciting new design concepts in structural industry from airport terminals to shopping malls, office buildings to domed stadiums, convention centres to residential housing. In addition, hollow sections, which are extremely desirable as a column for construction, are structurally more efficient compare to open sections because of high strength to weight ratio, uniformity, increased fire resistance and an excellent torsional resistance. Practically, hollow structural sections can readily be bent, formed, punched and drilled, and they are environmental friendly as they are made from steel, one of the world's most recyclable material. Turning to connection area between hollow sections and other structural members, this is the dominance difficulty which is restricted application of this section from use. The problem is hollow sections have a lack of access from inside for tightening the nut of the bolt.

As far as connection between hollow section and open section is concerned, several investigations have been carried out so as to overcome this issue. Over the years, many alternatives are proposed such as additional plates and fully welded connection but they are not convincing because of complicated manufacturing procedure, quality issue, impractical and high cost. Regarding, arisen issue in the field of engineering to make a connection in one side resulted in development of many type of connectors. Presently, scant attention has been paid to a new technique of connector which is using blind bolts. This bolt can be tightened in one side that makes it viable to connect open and hollow section. Up to date, limited information is available on the behaviour of this bolt. Therefore, more exploration is needed to fill those gaps which exist in the area of blind bolted connection.

Many types of blind bolts have been developed for open section steel beams to hollow section columns connection such as Flowdrill, Ajax on side and Lindapter hollo-bolt (HB). More recently, at the Nottingham University, modification has been made in the Linapter hollo-bolt which was an extension in the shank length and adding nut at the end of the bolt, it is labelled Extended Hollobolt (EHB). The application of this novel connector is for connecting concrete filled hollow section with other structural members. The purpose of this modification is to extend application of this fastener in moment resisting connection. It is obvious that the loading of these connections is such that some of the fasteners will be subjected to both tension and shear. Such combined effects are also typical of the stresses to which wind-bracing fasteners may be subjected. Thus, it is necessary that information be available on the strength and characteristic behaviour of Extended hollo-bolts are subjected to combined tension and shear forces.

1.1 Research Justification

Blind-bolts have been developed to allow for bolted connection to steel hollow sections. Up to date, they have been investigated for pure shear and pure tension alone, limiting their application to simple (pinned) joints. Also, from practical point of view, in many bolted connections, fasteners are subjected to a combination of tension and shear loading. Thus, to extend their use in moment-resisting connections, there is a need to understand the behaviour of the bolt under combined tension and shear forces. Notably, the consequences not only contribute to knowledge about the behaviour of the blind bolt under different combination of tension and shear forces, but also based on the behavior observed and analysis of the test data, this work formulated new design recommendations for use in calculating the design capacity of EHB connections subject to combined tension and shear. In addition, this study dispenses guidance for further investigation in this area.

1.2 Aim and Objectives

The aim of this research is to ascertain the strength and characteristic behaviour of single extended hollo-bolt (EHB) connection to concrete filled hollow section when subjected to various combinations of tension and shear ratio, and to compare those results to the strength and behaviour of standard bolts, whether the current standard rules can be used for EHB.

The hypothesis of this research is that combined tension and shear interaction model for the EHB can be modelled by experimental data.

The primary objectives of this research are:

- Review the state of art of blind bolted connection
- Design an experimental setup allowing for the application various ratios of tension and shear force.
- Carry out an research work to determine the strength of EHB when subjected to combined tension and shear forces.
- Propose interaction model for the EHB under different combination of tension and shear forces.

1.3 Research Methodology

The following steps will be made so as to achieve the objectives of the research which led to fulfilment of the aim.

- Review of existing knowledge in the field of EHB connection led to investigate into strength of the bolt and directed the project towards an experimentally based investigation. Test parameters are also determined which of the driving and testing conditions require careful control and, to some extent, which variables need to be studied further.
- Design an experimental setup which includes defining test parameters which are involving in the test program such as EHB properties, concrete grade and plate thickness. Also, design an appropriate test setup which is to obtain the ultimate strength and characteristics behaviour of EHB subjected to loadings at many different shear-tension ratios. The scheduled test program includes loadings at only four different shear-tension ratios. This larger variety of shear-tension ratios made it possible to study in greater detail.

1.4 Overview of the Research

The purpose of this section is to demonstrate the structure of this research, which starts by the introduction above. The literature review which is to review the current knowledge so as to determine the research proposal of this study. At the beginning, the basic information which related to this research is reviewed. The existing knowledge of the performance of the Lindapeter HB is presented based upon previous investigation. The overview of the development of the Extended Hollo-bolt (EHB), which is developed at the University of

Nottingham, is summarised. The determination of the theoretical characteristic strength of bolts and the standard design equations are shown, and then the historical background of current standard equations for bolts under combined tension and shear ratios are is evaluated with respect to Eurocode 3, German DIN and British standard.

2 LITERATURE REVIEW

The purpose of this research is to review published information in the area of blind bolted connection to structural steel hollow section and identify those areas which require further investigations. The review starts to present background information on the classification of joins and then summarises the concept of component method. The results of an experimental programme for the commercially available Lindapter 'Hollo-bolt' will be examined with respect to its performance in the connection. Released knowledge on Hollo-bolt, directed the modification of the bolt which carried out at the University of Nottingham, the bolt is named Extended holl-bolt and it has a significant stiffness compare to the original one. Although an accurate theoretical analysis to determine strength of individual fasteners subjected to shear or tension separately is difficult, Eurocode 3 provides rules for tension and shear resistance of bolts by conducting statistical evaluation of test results. At the end, strength and characteristic behaviour of bolts under combined loading will be discussed based upon current standard interaction model.

2.1 Structural Joints

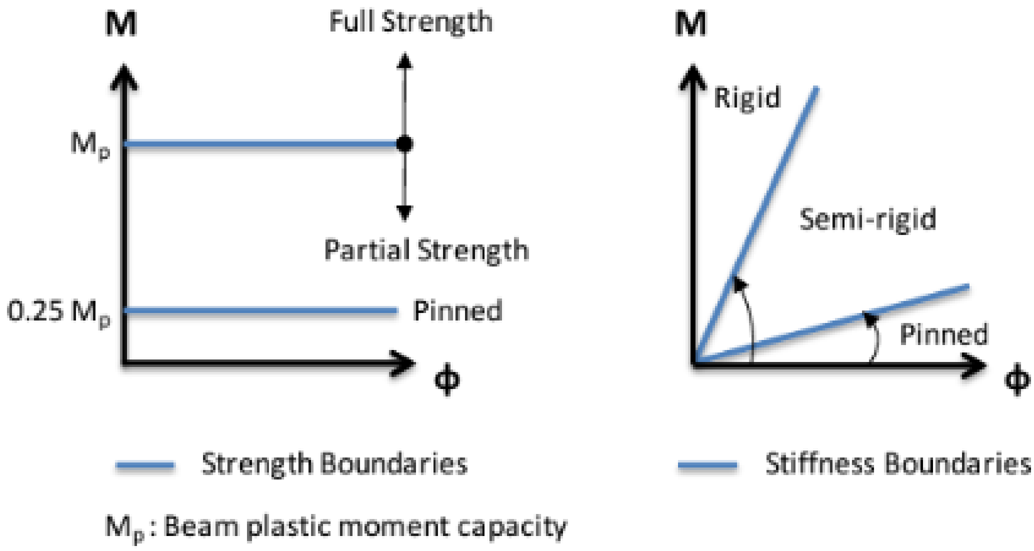
Two terms need to be defined which are connection and joint. Connection is an area where two members meet and they are connected by fasteners such as weld, rivet, and bolt. Joints characterise a zone which include the connection and a portion of elements (Trahair, Bradford et al. 2008). Each component in the joint has its own strength and stiffness and contributes to the moment-rotation characteristics (Rueda Romero 2010). The ability of a connection to transfer loads over an extended period of time, or during a seismic event, has a direct effect on the reliability, safety, and durability of the structures.

2.1.1 Joint classification

Joints can be classified according to strength, stiffness as well as ductility. In addition, CEN. 2005 classifies joints according to their stiffness and strength. Obviously, different classification might be found in various sources because limited information is available in this area. Generally, Joints, which are nominally pinned, rigid and semi-rigid, can be defined based on initial rotational stiffness of the joint. Classification boundaries of the joint based on stiffness are shown in Figure 2.1(b):

As far as strength classification is concerned, joint strength boundaries depends on the design moment resistance of a connection and connected members. This can be classified under three categories which are nominally pinned joint, full strength joint and partial strength joint (CEN. 2005), these are shown in Figure 2.1(a).

Based upon the EC3 definition, nominally pinned joint can transmit internal force because the strength of this joint is below 0.25Mp while the efficacy of full strength joint is more than the strength of connected members. And, any strength between those two criteria is classified as a partial strength.



(a) By strength (b) By stiffness

Figure 2-1 Joint classification (CEN.2005)

Zone 1: Rigid, if

$$S_{j,int.} \geq \frac{k_b E\, I_b}{L_b} \quad \ldots\ldots 2.1.1$$

This joint can resist applied moment because of adequate rotational stiffness.

Zone 2: Semi-rigid,

Those criteria which are between rigid and nominally pinned are semi-rigid. This joint can transfer internal force and some moments between beam and column.

Zone 3: Nominally pinned, if

$$S_{j,int.} \leq \frac{0.5\ E\, I_b}{L_b} \quad \ldots\ldots 2.1.2$$

It is only designed to transmit shear force from beam to column.

Where:

$S_{j,int.}$ is the initial rotation stiffness

K_b is related to the bracing system in the building k_b: 8 for braced frame

k_b: 25 for un-braced frame

I_b is the second moment of area of a beam

L_b is the length of a beam (centre to centre)

E is the modulus of elasticity of steel

2.1.2 Component method

The prediction of the Moment-rotation response of structural joints often requires a non-linear procedure which is likely to be very complex. Therefore, component method, which is a simple approach to predict steel joint response, has been developed. On the whole, Weynand, Jaspart and Ly (2003) describes that "the originality of component method is to consider any joint as a set of individual components". In other words, It seems that this method is widely accepted because EC3 provides a guidance to predict the rotational behaviour of joints based on basic components.

Joints in steel structures comprise of several properties of material such as columns, plates, bolts and beams. This method determines the behaviour of joints based on property of components in respect to moment capacity, stiffness and deformation capacity (Rueda Romero 2010). The determination of the assembly of mechanical properties of each basic component leads to the properties of the whole joint. That assembly should be based on satisfying equilibrium conditions of the joint. As a rule, CEN (2005) indicates that basic components in the joint determine the resistance of that joint.

One of the advantages of component method is that it allows mixed joint configuration (Weynand, Jaspart and Ly 2003). However, this method has its own limitations such as design rules for evaluation of some basic components might not be applicable and an accurate assembly procedure might not be available (Pitrakkos 2012).

Weynand, Jaspart and Ly (2003) identified that component method requires three major steps which are identification of the component, specify the mechanical behaviour of each component and combination all components together to form the moment-deformation of the whole joint. Figure 2.2 illustrates the steps of component method for the steel joint.

Rueda (2010) determines that basic component functions are depend on the joint configuration and loading. For example, end plate joint is divided into three zones which are tension, compression and shear. As it can be seen in Figure 2.3 Basic components are specified based on three zones, each component contributes to the overall deformation and capacity of the joint. To be more precise, altering applied force and configuration of the joint would change the whole function of components. For instance, bolts are subjected to both tension and shear in joints which contain inclined members.

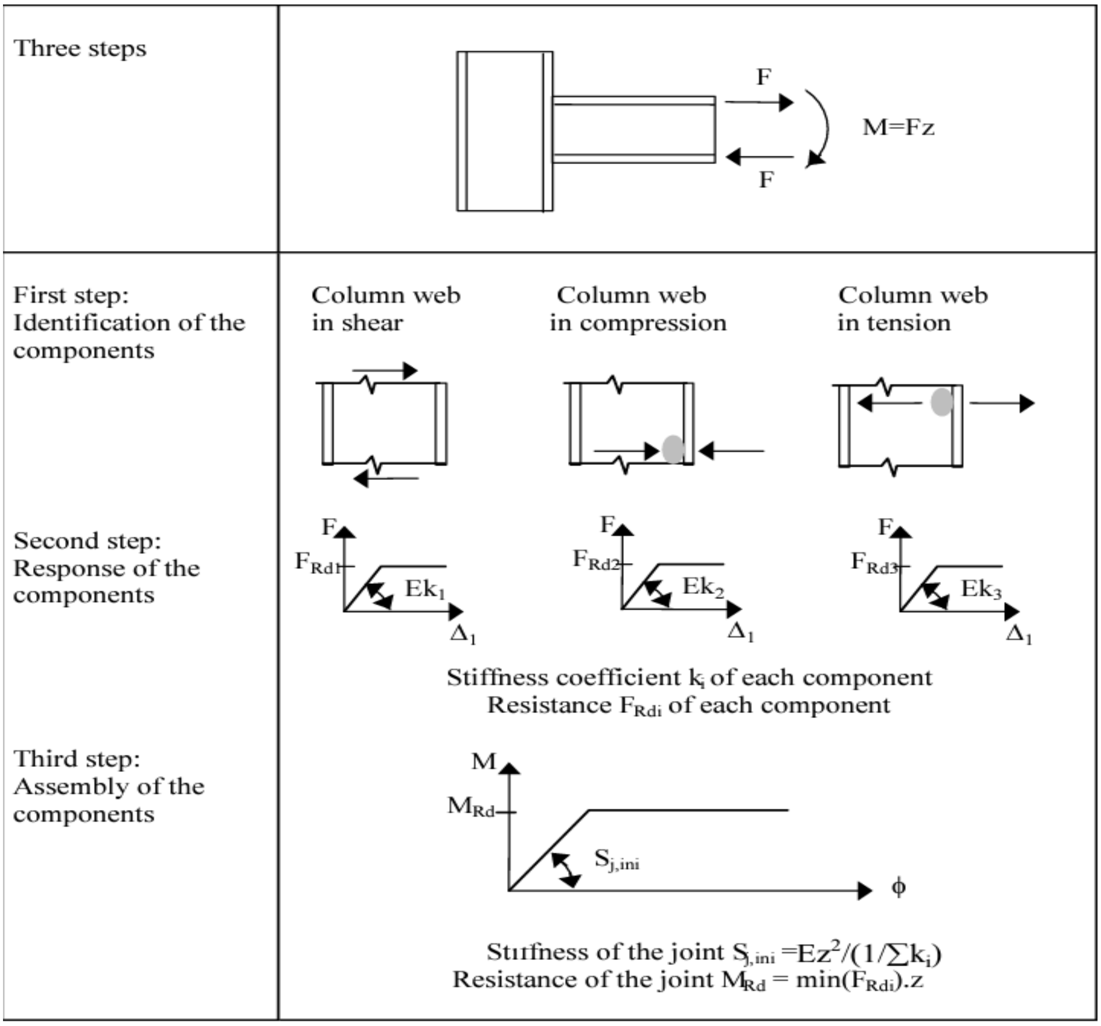


Figure 2-2 Component method application (CEN. 2005)

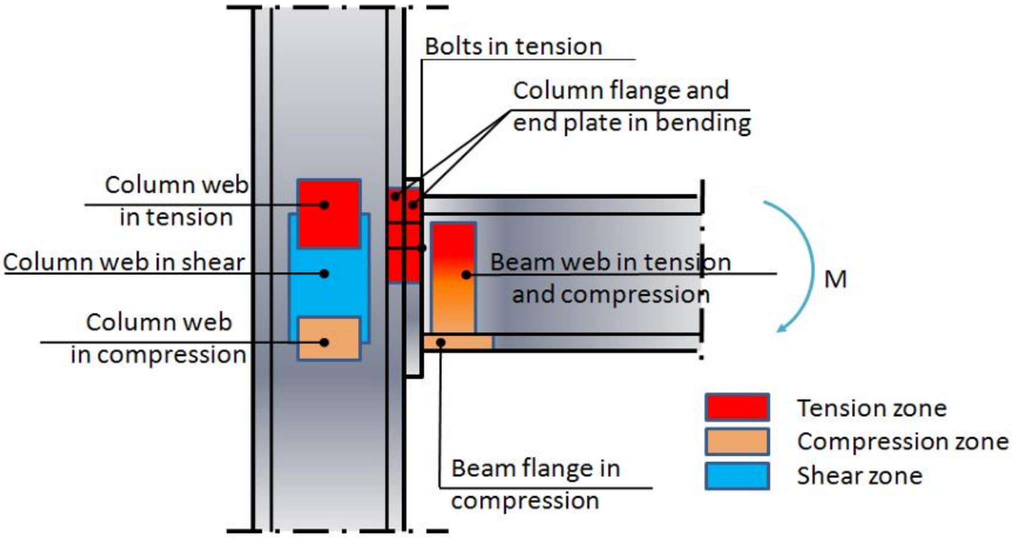


Figure 2-3

Basic components in beam-column connection in bending (CEN.2005)

2.1.3 Bolts in component method

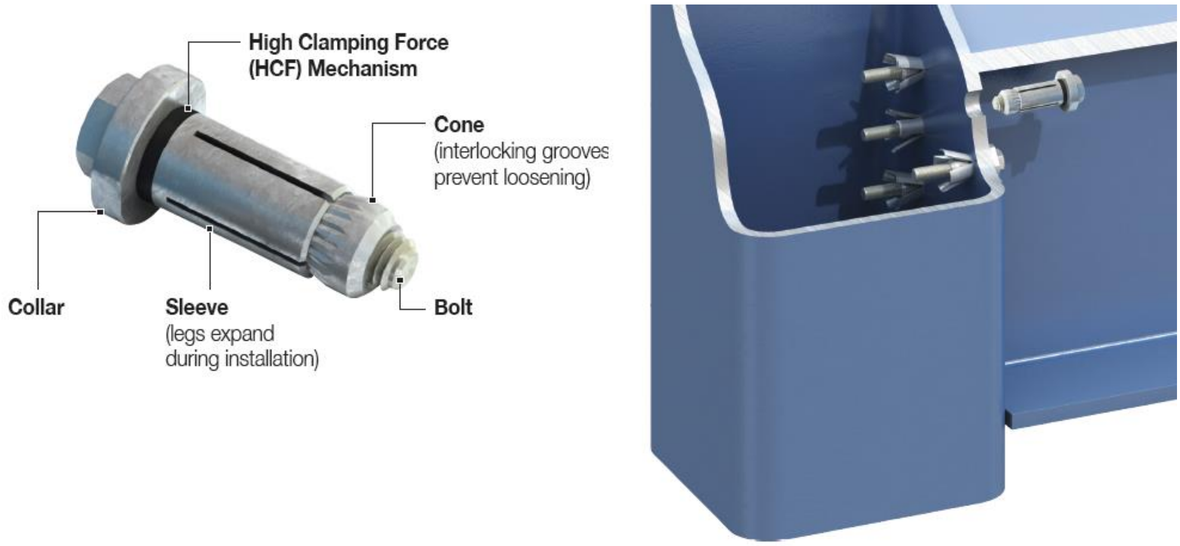
The joints can be varied based upon member thickness, material, bolt diameter, number of bolts, and placement of bolts. Specifically bolts can be arranged in multiple rows with several bolts per row or bolts may be staggered A critical aspect to the understanding of the overall response of bolted connections under loadings lies in the characteristic behaviour of single bolts. Regarding, blind bolt, which is a sort of a bolt to overcome the issue of connection between open and hollow steel section, has its own performance in the connection. Standard codes do not provide the response of this component under different loading such as tension, shear and combined shear and tension loading. Therefore, for justification of this bolt to use in the connection, the behaviour of this basic component should be well-known. Up until now, both holl-bolt (HB) and Extended hollo-bolt (EHB) as a basic component in the overall response of joints are under investigation to fill that gap in the standard codes.

2.2 Lindapter Hollo-bolt (HB)

Ellison and Tizani (2004) mentioned that arisen issue in the field of engineering to make a connection in one side resulted in development of many type of connections such as blind bolted connection. This bolt can be tightened in one side that makes it viable to connect open and hollow section. The review of Lindapter Hollobolt, which is a type of blind bolt, is chosen because the bolt is commercially available and the modification of this bolt will be investigated in this research.

Hollobolt is labelled a Lindapter 5-piece because it comprises of 5 components, Figure 2.3 depicts parts of HB and applications between open and hollow section. One of the viable features of HB is that the installation is simple in a way that it can be installed in site without special technician

Figure 2-4 HB components and applications to hollow section (Lindapter 2013)



Many investigations have been conducted in order to explore the behaviour of Hollobolt. It was concluded that HB has a low stiffness compare to a normal bolt connection (Al-Mughairi 2009). Wang, Tizani and Wang (2010) indicated that stiffness of HB is less than the stiffness of standard bolts and demonstrated that strength and stiffness of blind bolted connection is apparently affected by the flange thickness rather than the bolt itself.

Wang, Han and Uy (2009) confirmed that plate thickness affects the strength and stiffness of the connection. Figure 2.4 shows the effect of flange thickness in connection, it can be seen that capacity of connection is proportional to plate thickness.

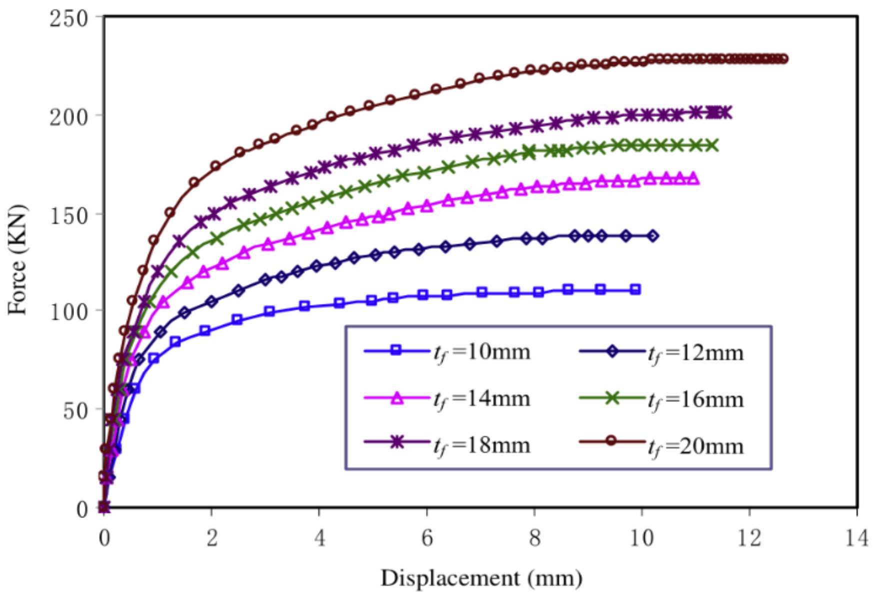
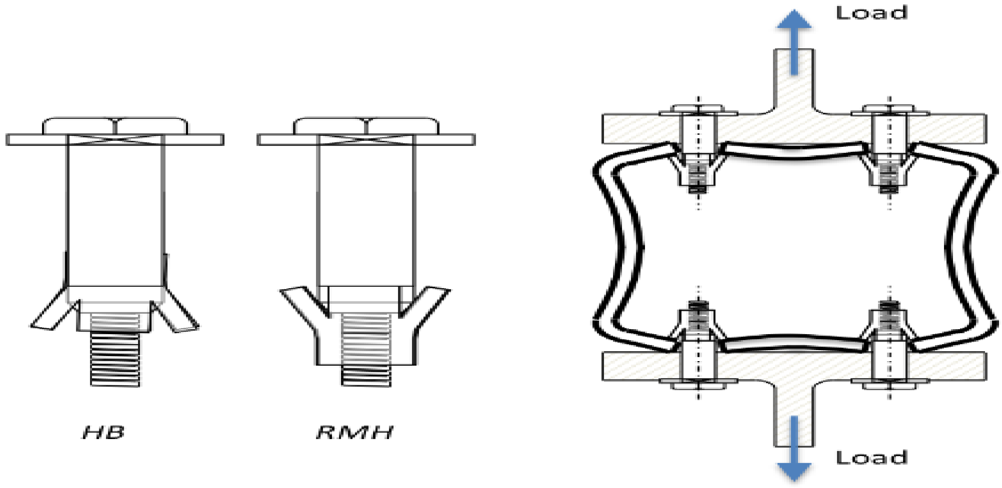


Figure 2-5 Flange thickness influence on force-displacement curve M16 (Wang *et al*. 2010)

Pitrakkos (2012) demonstrated that HB connection between open and hollow member under tensile force resulted in two modes of failure which are pulling out failure and shear failure in the flared legs of the bolt. However, Wang, Han and Uy (2009) showed that HB can perform well in connection to concrete infill hollow section and no sign of failure observed with respect to shear deformation and bending of the bolt.

Elghazouli et al. (2009) stated that deformation of sleeves resulted in the separation between two plates and fracture and crush of sleeves occurred at final failure. On the other hand, Al-Mughairi (2009) observed early separation between flanges of the T-Stub because of ductility in the shear legs.

Test results showed that HB cannot resist clamping force, therefore connections might subject to failure in both pulling-out and shear in the sleeves. Thus, modification was done by inverting the sleeves of standard HB Figure 2.5(A), and it is labelled Reverse Mechanism Hollobolt (RMH). Research showed that higher stiffness can be achieved in the RMH connection. On the contrary, the extensive deformation in the tube wall was observed as shown in Figure 2.5(B) and sudden failure was observed in the legs.



(a) Modification of HB to RMH (b) Tube face deformation

Figure 2-6 HB modification and face deformation (Pitrakkos 2012)

Research has shown that aforementioned blind bolts have capacity to resist shear load and limited tensile force (Ellison and Tizani 2004). However, those bolts do not have adequate stiffness to moment in connection. As a result of that, the standard HB has been modified at the University of Nottingham which was an extension in the shank length and adding nut to the HB, it is named extended hollobolt (EHB). Figure 2.6 shows the modification of standard HB for both Reverse mechanism and EHB. These changes are done after indicating the weak spots of the bolt in the investigation. The EHB is currently under investigation to determine the behaviour of the bolt in the concrete filled hollow section.

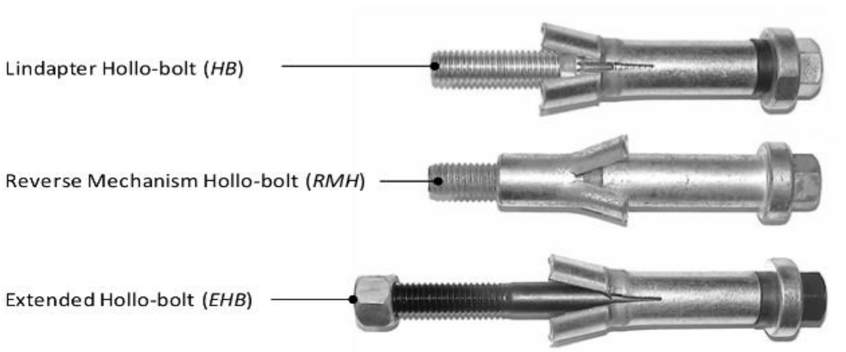


Figure 2-7 HB modifications (Pitrakkos 2012)

Test results showed that this novel type of blind bolt can resist a noticeable tensile force. In addition the moment resisting connection can be achieved by using this new blind bolt in concrete filled hollow section.

Further investigations have been carried out on EHB under cyclic loading procedure so as to explore the behaviour of the connection in terms of tube wall thickness, concrete grade and bolt grade. The stiffness and tensile resistance of the joint is increased by using EHB because the shank of the bolt is anchored in the concrete

(Tizani, Wang and Hajirasouliha 2012). Wang and Chen (2012) demonstrated that providing anchorage extension to the blind bolted connection can enhance the strength and stiffness of the connection.

Ellison and Tizani (2004) carried out a test for comparison between modifications of HB and standard bolt to concrete filled hollow section. The same failure which was bolt shank fracture was observed in the standard bolt, HB and EHB whereas the Failure in RMH was a pull-out of the bolt this is because of failure in the legs, summary of displacement and failure mode are shown in Table 2.2.

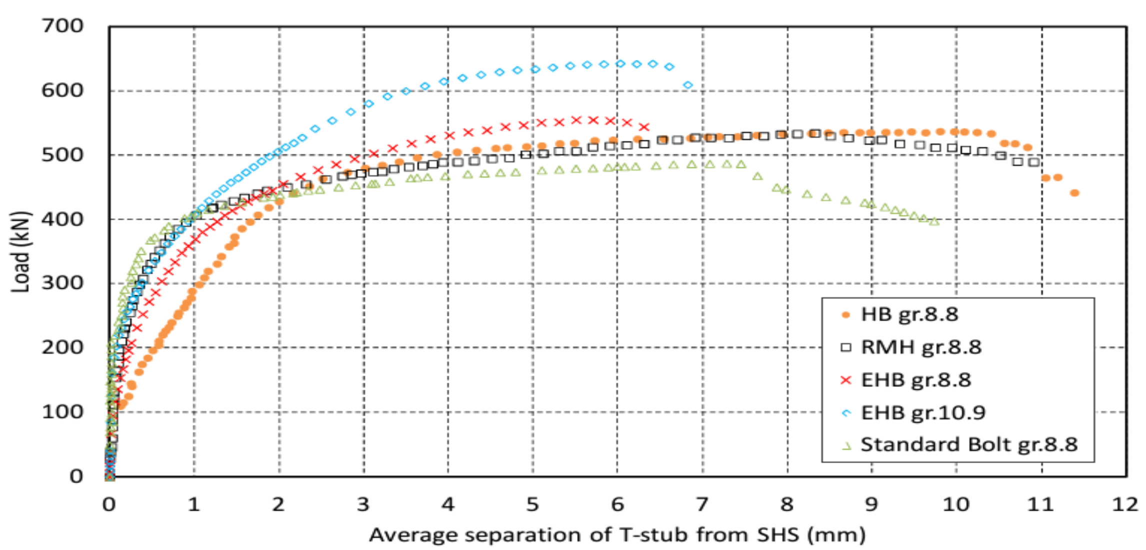
Table 2-1 Displacements and failure mode of HB, RMH, EHB and standard bolt (Ellison and Tizani 2004)

Bolt type	**Ultimate (kN)**	**Displacement at ultimate load**	**Failure mode**
Standard	487.5	7.5	Bolt shank fracture
Hollo-bolt	536.3	10.5	Bolt shank fracture
RMH	535.6	8.5	Bolt pull-out
Extended Hollo-bolt	624.5	5.5	Bolt shank fracture

2.3 Reviews on EHB Connection to Concrete Filled Hollow Section

In order to investigate behaviour of Extended Hollobolt (EHB), Ellison (2003) and Pitrakkos (2008) carried out a test on the connection of T-stub to concrete filled hollow section for EHB, Hollobolt, RMH and standard bolt. The average separation of T-stub is illustrated in Figure 2.7, it can be seen that EHB connection is below the capacity of standard bolted connection and recorded less separation compare to other blind bolts. It was concluded that the stiffness of EHB connection is higher among others that is because anchor nut and longer shank provided extra bond and anchorage. In other words, Al-Mughairi (2009) observes that moment capacity of EHB connection increased because of bolt shank extension. Ellsion and Tizani (2004) indicated that the EHB connection can be classified under rigid connection because the modification stiffens the connection.

Figure 2-8 Results of t-stub connection to concrete filled hollow section (Pitrakkos 2008,Ellison 2003)



Al-Mughairi, Tizani, and Owen (2009) investigated in the behaviour of the EHB connection to infill concrete hollow section, observed that tube wall thickness, endplate, concrete grade and bolt pitch contribute to stiffness and capacity of the connection.

In addition, Al-Mughairi (2009) indicated that EHB offers an adequate strength to pull-out compare to HB. Also, pointed out that changing concrete strength has a slight effect on connection behaviour. Similarly, Al-Mughairi, Tizani, and Owen (2009) reported that concrete strength does not have a primary effect on the behaviour of the connection and illustrated the relationship between rotation and moment of the connection with two various grades of concrete which is C40 and C60 as shown in Figure 2.8.

However, Tizani, Wang and Hajirasouliha (2012) demonstrated that “Any decrease in tube wall thickness and concrete grade is normally accompanied by a decrease in the strength and stiffness of the connection”.Pitrakos (2012) confirmed that the difference in the concrete grade predominantly influence on the stiffness of the EHB components.

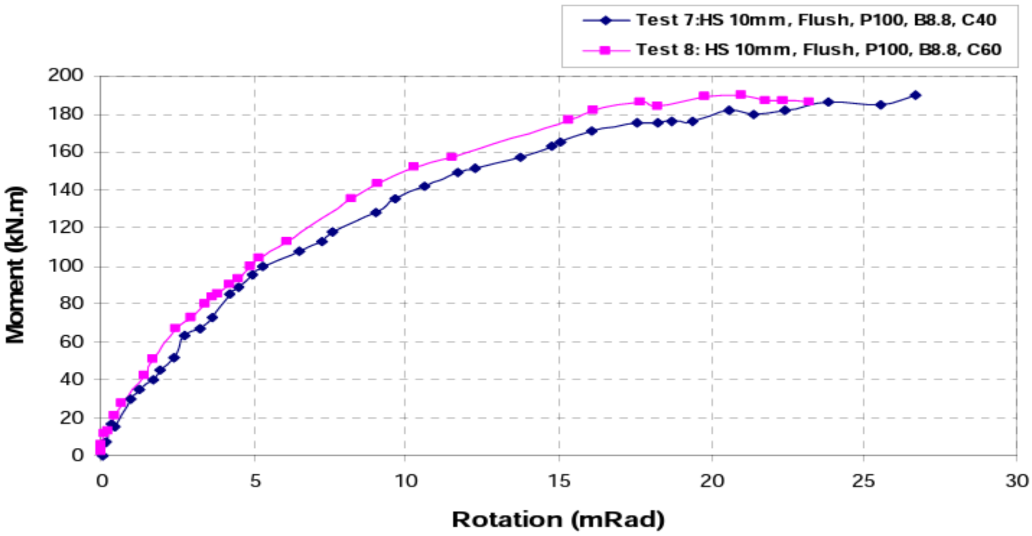


Figure 2-9 Moment rotation curve for two grades of concrete (C40 and C60) (Al-Mughairi, Tizani, and Owen 2009)

Al-Mughairi, Tizani, and Owen (2009) tested three connections with different thickness of tube (8mm, 10mm, 12.5mm), demonstrated that the moment capacity is quite matching and initial stiffness is almost the same for all of them. Whereas, yielding in the 8mm thickness was observed before the final failure. Tizani, Wang and Hajirasouliha (2012) carried out a test on using EHB with different tube thickness and observed two failure modes which are bolt fracture and moderate face deformation of the tube.

Up to date investigations has concluded some points as follows. It was indicated that reducing tube thickness can change the bolt fracture failure to tube face failure and might result in decreasing of stiffness and strength. Pitrakos (2012) summarised that the stiffness of EHB is higher than the Lindapter HB this is because of the mechanical bond between the component of EHB and the concrete.

Pitrakos (2012) indicates that bolt diameter has a considerable effect on the strength and stiffness of the connection. Also, concluded that embedded depth cannot have a major influence on the stiffness, strength, ductility and ultimate failure of the EHB elements.

So far, most of investigations have focused on understanding the behaviour of blind bolted connection in terms of stiffness, moment resisting and performance of the bolt under tension and shear separately. However, Yamaguchi *et al.* (2004) states that generally, connections should have enough capacity to resist actual load combinations. In this point of view, overall connection might be subjected to combined tension and shear.

Therefore, further investigations might primarily focus on the strength and characteristic of this bolt under combination shear and tension. It would be said that judgement on performance of EHB under combined mechanism might be difficult since concrete and other factors contribute to connection configuration.

2.4 Theoretical Resistance of Bolts

Bolted connection is more common in steel structures because of build-ability and ease of fabrication. Trahair *et al.* (2008) state that the performance of a bolted connection is complicated and both the stress distribution in the connection and the forces in the bolts are dependent on the stiffness of the bolts, and the connecting steel elements. Consequently, an exact theoretical analysis is not possible. Furthermore, the design of a bolted connection is semi-empirical, namely based on past experience of good performance, custom and practice, but always validated with a statistical evaluation of test results. For example, CEN. (2005) provides design resistance for individual connectors for shear resistance, tension resistance, and combined tension and shear based on statistical evaluation.

2.4.1 Bolt characteristics

The basic mechanical properties of bolts which should be adopted as characteristic values in design calculation are shown in Table 2.1 (EC3 2005). All of these bolt grades are generally used in connections subject to static forces and moments. During design, the weakest section of a bolt, which is a threaded portion of a bolt, should be considered. Therefore, the strength of the bolt is usually computed by using the tensile stress area defined by the core and nominal diameter of the bolt as pictured in Figure 2.3.

Table 2-2 Yield and ultimate tensile strength for bolts (EN 1993-1-8 table 3.1)

Bolt classes	**4.6**	**5.6**	**8.8**	**10.9**
f_{yb} (N/mm^2)	240	300	640	900
f_{ub} (N/mm^2)	400	500	800	1000

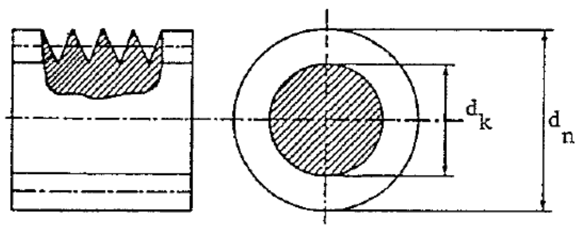


Figure 2-10 Definition of stress area

$$\text{Tensile stress area } (A_s) = \frac{\pi}{4}\left(\frac{d_n + 3.d_k}{4}\right)^2 \ldots\ldots 2.4.1$$

Where:

d_n is the nominal bolt diameter

d_k is the core diameter of bolt

2.4.2 Tensile strength

When a tensile load applied to a bolt, failure occurs in the threaded part because of the reduction in the tensile stress area. Thus, the tensile strength of a bolt is determined based upon the reduced area. The equation, which is internationally standardised, is

$$F_{ts} = f_{ub} \text{ x } A_s \ldots\ldots 2.4.2.1a$$

The design equation for this failure mechanism has been presented as follows

$$F_{td} = \frac{f_{ub} \text{ x } A_s}{\gamma_m} \ldots\ldots 2.4.2.1b$$

Based upon the statistical analysis by Snijder, H. et al (1988), the theoretical resistance of a bolt under tensile force has been changed into

$$F_{ts} = 0.9\, f_{ub} \text{ x } A_s \ldots\ldots 2.4.2.2a$$

They also harmonised a design safety factor value (γ_m)which is 1.25 for all bolts. Consequently, resulting in the following design equation for bolts

$$F_{td} = \frac{0.9\, f_{ub} \text{ x } A_s}{\gamma_m} \ldots\ldots 2.4.2.2b$$

Where:

F_{ts} is the strength function for a bolt in tension

F_{td} is the design strength for a bolt in tension

f_{ub} is the ultimate tensile strength of the bolt material

A_s is the area of threaded portion

γ_m is the partial safety factor

2.4.3 Shear strength

The failure mechanism of bolts under pure shear depends on the location of the shear plane, shear plane may pass through the shank of the bolt or threaded portion. However, in general the shear strength of bolts is calculated based on the pure shear strength of the bolt material. Based on experimental evident, the pure shear strength is taken as 0.7 f_{ub} (Snijder H. et al 1980). The following cases are taken into account

Case 1: Shear failure in the shank of the bolt

For this case, the strength equation for bolts under shear can be written

$$F_{vs} = 0.7\, f_{ub}\, A \quad \ldots \ldots \quad 2.4.3.1a$$

The design equation for this failure mechanism has been presented as follows

$$F_{vd} = \frac{0.7\, f_{ub}\, A}{\gamma_m} \quad \ldots \ldots \quad 2.4.3.1b$$

Based upon the statistical analysis by Snijder, H. et al (1988), the theoretical resistance of a bolt under pure shear force has been changed into

$$F_{vs} = 0.6\, f_{ub}\, A \quad \ldots \ldots \quad 2.4.3.2a$$

Resulting in the following design equation

$$F_{vd} = \frac{0.6\, f_{ub}\, A}{\gamma_m} \quad \ldots \ldots \quad 2.4.3.2b$$

This equation is applicable for all bolt grades

Where:

F_{vs} is the strength function for a bolt in shear

F_{vd} is the design strength for a bolt in shear

f_{ub} is the ultimate tensile strength of the bolt material

A is the cross – section of the shank of the bolt

γ_m is the partial safety factor

Case 2: Shear failure in the threaded portion

For this case, the strength equation for the bolt is relatively analogous to the aforementioned strength equation. However, instead of the cross-section of the shank the area of threaded portion (A_s) should be considered. Thus, the equation will change to

$$F_{vs} = 0.7\, f_{ub}\, A_s \quad \ldots \ldots \quad 2.4.3.3a$$

The design equation for this failure mechanism has been presented as follows

$$F_{vd} = \frac{0.7\ f_{ub}\ A_s}{\gamma_m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 2.4.3.3b$$

Based upon the statistical analysis by Snijder, H. et al (1988), the theoretical resistance of a bolt where the shear plane passed through the threaded portion is separated for two equations depending on the grade of the bolt. In the evaluation, it was attempted to adopt the same strength equation for both shear plane in the shank and shear plane in the threaded. However, that seemed to be impossible for bolt grade 10.9.

For the bolt grades 4.6, 5.6, and 8.8:

$$F_{vs} = 0.6\ f_{ub}\ A_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 2.4.3.4$$

For bolts grade 10.9:

$$F_{vs} = 0.5\ f_{ub}\ A_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 2.4.3.5$$

Resulting in the following design equations

For the bolt grades 4.6, 5.6, and 8.8:

$$F_{vd} = \frac{0.6\ f_{ub}\ A_s}{\gamma_m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 2.4.3.6$$

For bolts grade 10.9:

$$F_{vd} = \frac{0.5\ f_{ub}\ A_s}{\gamma_m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 2.4.3.7$$

2.5 Bolts under Combined Tension and Shear Loading

2.5.1 Failure mechanism

Although configurations of separate forces on bolts are available, estimating strength of bolts under combined loads would be difficult because of unsettled failure plane position. Owens and Cheal (1989) indicate that bolts might fail in combined tension and shear if shear plane cuts bolt shank. Alternatively, in the predominant tension over shear, failure may occur in the treaded portion when the shear plane cuts thread.

In the same way, Chesson, Faustino, and Munse (1964) observed that mechanism failure in thread depend on the tension and shear ratio and position of shear plane. Yamaguchi et. al. (2004) observed breaking of the bolt under combined loads at the threaded section while deformation due to shear force was no observed in the bolt. Figure 2.10 shows shear planes at bolts in both threaded part and shank.

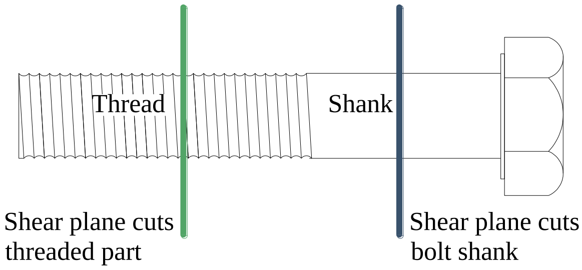


Figure 2-11 Shear planes at standard bolts

Considering states mentioned above, in order to obtain an accurate capacity of a bolt under combined shear and tension, shear plane should cut bolt shank. However, there is uncertainty about those probabilities because other factors influence on strength of bolts under combined loads (Yamaguchi et. al. 2004). As Chesson, Faustino, and Munse (1964) stated that length and grip of the bolt and material type might influence on the performance of the bolt under combined loads. Also, concluded that at the normal structures, the influence of bolt diameter to determine ultimate strength is negligible.

Regarding theoretical side of failure mechnism, NASA TM X-73305 (1975) used the maximum normal stress ($\sigma_{max.}$) and maximum shear stress ($\tau_{max.}$) theories to predict the ultimate failure of an element of a structure when is subjected to combined stresses such as tension, shear and compression. In this case, the interaction equation can be attained through the graphical construction of Mohr's circle, the principal stress equations can be used for combining normal stress (σ) and shear stress (τ). The maximum principle and shear stresses are given as follows considering these criteria:

Let the maximum shear stress ($\tau_{max.}$) be defined as the failing stress $\tau_{ult.}$

Let the maximum principle stress ($\sigma_{max.}$) be defined as the failing stress $\sigma_{ult.}$

Let $k = \frac{\tau_{ult.}}{\sigma_{ult.}}$, based on experimental data, the k value is vary from 0.5 to 0.75

Replace $\tau = R_s \text{ x } \tau_{ult.}$ *and* $\sigma = R_t \text{ x } \sigma_{ult.}$

Maximum normal stress theory

$$(\sigma_{max}) = \frac{\sigma}{2} + \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} \quad \ldots\ldots 2.5.1.1$$

$$1 = \frac{R_t}{2} + \sqrt{\left(\frac{R_t}{2}\right)^2 + (k\,.\,R_s)^2} \quad \ldots\ldots 2.5.1.2$$

Maximum shear stress theory

$$(\tau_{max}) = \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} \quad \ldots\ldots 2.5.1.3$$

$$1 = \sqrt{\left(\frac{R_t}{2k}\right)^2 + (R_s)^2} \quad \ldots\ldots\ldots 2.5.1.4$$

The notation of R_s stands for shear load ratio, and R_t is for tension load ratio

The criterion usually cited for a member loaded in combined shear and tension is when the k value is equal to 0.5. Thus, the above equations simplify to the following interaction equations

Substituting the value of k in maximum normal stress resulted in

$$2 = R_t + \sqrt{{R_t}^2 + {R_s}^2} \quad \ldots\ldots\ldots 2.5.1.5$$

Substituting the value of k in maximum shear stress resulted in

$$1 = {R_t}^2 + {R_s}^2 \quad \ldots\ldots\ldots 2.5.1.6$$

From the above analysis, the equation 2.5.1.6 is valid for all values of R_t and R_s. Also, it is conservatively safe and convenient to use the maximum shear stress equation with k=0.5. As a result, the theoretical approach to interaction model resulted in the following equation

$${R_t}^2 + {R_s}^2 = 1 \quad \ldots\ldots\ldots 2.5.1.7$$

The above equation is stress based criterion whereas the general form for the interaction equation is often used as a load based criterion. Therefore, it is reasonable to replace the normal stress (σ) to a normal load (F_t), the shear stress (τ) to a shear load (F_v), and material allowable stresses ($\sigma_{ult.}$) and ($\tau_{ult.}$) to allowable loads (F_{ts}) and (F_{vs}) as follows which correlates with quadratic equation that used in the German standard (DIN)

$$\left(\frac{F_t}{F_{ts}}\right)^2 + \left(\frac{F_v}{F_{vs}}\right)^2 = 1 \quad \ldots\ldots\ldots 2.5.1.8$$

where

F_t , F_v are the tension and shear componets in the bolt respectively

F_{td} , F_{vd} are the design strength for a bolt under pure tension and pure shear respectively

2.5.2 Evaluation of current standard codes

Speaking generally, in structural connections, bolts are often exposed to combination of shear and tension loads. However, they were often investigated for either tension or shear loads separately, that is because conducting an experiment for combined loading is not easy. Thus, the rules in the standards such as DIN, EC3 and BS standards are based on general assumptions because of unavailable experimental data. During assembling EC3, Snijder H. et al (1980) carried out a statistical evaluation based on a few number of tests and observed that current combining functions may not be on the safe side. After that the interaction equation was altered into a much more conservative version. Figure 2.11 shows a different interaction models. It can be seen that the British standard equation and the German DIN describe nearly the same relation while the new Eurocode equation is much more conservative, in the case of using EC3 rule for design can lead to 50% more bolts for load situations with similar amounts of tension and shear. In the British standard, it is suggested to use a tri-linear design function for easier handling.

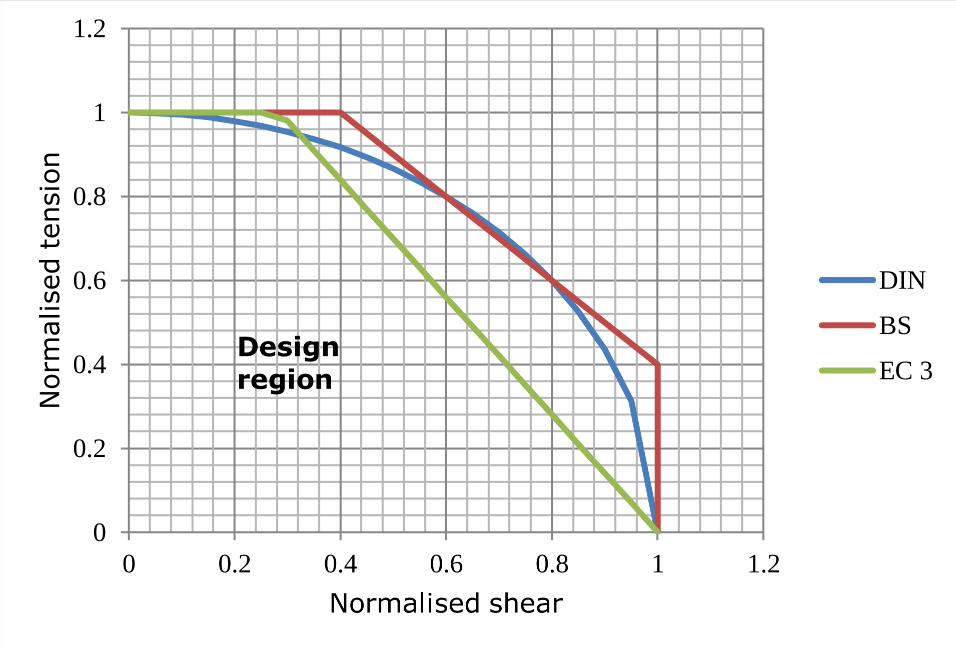


Figure 2-12 Comparison of interaction equations in EC3, BS and DIN standard

German DIN

$$\left(\frac{F_t}{F_{td}}\right)^2 + \left(\frac{F_v}{F_{vd}}\right)^2 \leq 1.0 \qquad 2.5.2.1$$

British Standard

$$\frac{F_t}{F_{td}} \leq 1.0 \qquad 2.5.2.2a$$

$$\frac{F_t}{F_{td}} + \frac{F_v}{F_{vd}} \leq 1.4 \qquad 2.5.2.2b$$

$$\frac{F_v}{F_{vd}} \leq 1.0 \qquad 2.5.2.2c$$

Eurocode 3

$$\frac{F_t}{1.4\, F_{td}} + \frac{F_v}{F_{vd}} \leq 1.0 \qquad 2.5.2.3$$

Where:

F_t , F_v is the tension and shear componets in the bolt respectively

F_{td} , F_{vd} are the design strength for a bolt under pure tension and pure shear respectively

The interaction equations for the German DIN, British standard and Eurocode, which are shown above, are attained for bolts under the combination of tension and shear loadings. This part of literature is to assess the validity of the old and new standard rules and the evaluation of current design rules for bolts based on theoretical and experimental background which is available up until now.

2.5.3 Theoretical and experimental background to the German DIN rule

The standards did not provide any rules for combined tension and shear until the end 1980s. Therefore, when the engineers encounter the combined loading in structural connections, they have to find a way of handling this. The common method in the past to solve this issue was to verify tension and shear load separately and the influence of a combined appearance was neglected. This solution did not affect the safety of the design because the standard loadbearing strengths for bolts were on the safe side. When the use of bolts continually gained acceptance as a structural fastener in both shop and field assembly of structural members, it became priority to provide rules for bolt design more economically and factoring the influence of both forces on each other in the calculation.

To achieve the combined tension and shear equation for bolts theoretically, it was considered the bolt as a round piece of steel that was subjected to a constant normal stress and shear stress over its cross section. Herein, the interaction equation can be used between both stresses and the equivalent stress can be found and compare it with the yield stress. In the following the derivation of the quadratic function is shown by idealisation the bolt as a round section of beam.

Forces:

Tension force component $(F_t) \rightarrow \sigma_x$

Shear force force component $(F_v) \rightarrow \tau_{xy}$

equivalent stress:

$$\sigma_e = \sqrt{(\sigma_x)^2 + 3.\left(\tau_{xy}\right)^2} \leq f_y$$

The factor $\sqrt{3}$ in the equation characterises the ratio between maximum permissible normal and shear stress.

$$\frac{(\sigma_x)^2}{\left(f_y\right)^2} + \frac{3.\left(\tau_{xy}\right)^2}{\left(f_y\right)^2} \leq 1.0$$

With relating stresses:

$$\left(\frac{\sigma_x}{f_y}\right)^2 + \left(\frac{\tau_{xy}}{\tau_R}\right)^2 \leq 1.0$$

When this equation is expanded by section area, it will result in the following equation. On the other hand, it is more convenient to alter the equation from stresses to permissible forces because it can be provided in tabular form and is easy to use. Therefore, the interaction equation would be

$$\left(\frac{F_t}{F_{td}}\right)^2 + \left(\frac{F_v}{F_{vd}}\right)^2 \leq 1.0 \quad \text{2.5.2.4}$$

Where

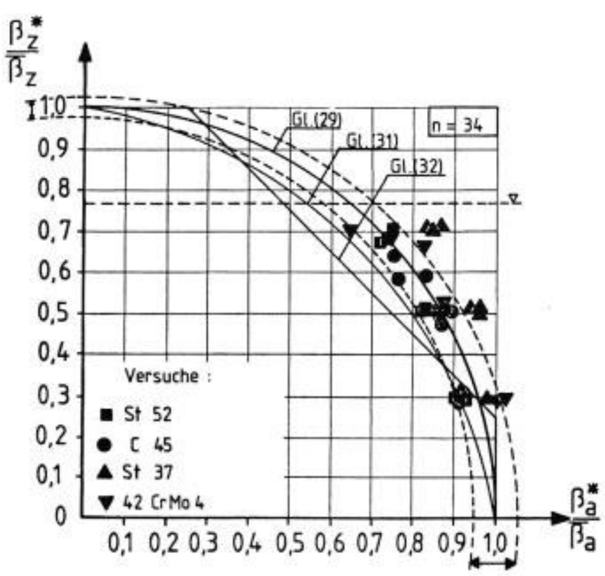
F_t , F_v is the tension and shear componets in the bolt respectively

F_{td} , F_{vd} are the design strength for a bolt under pure tension and pure shear respectively

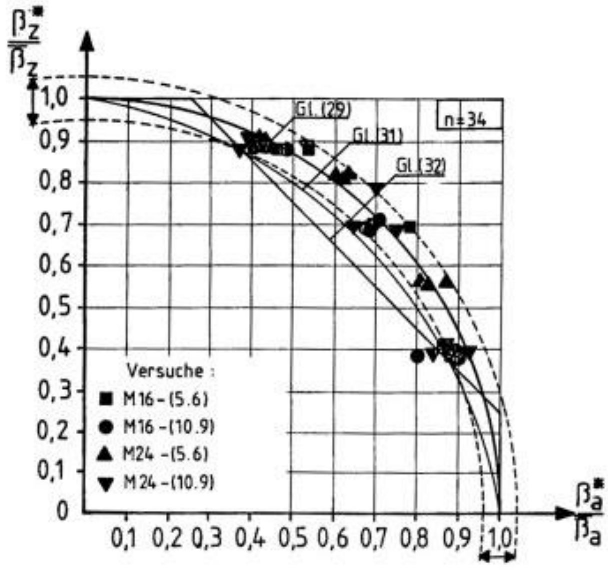
Regarding experimental background for German DIN, Hassler, M. (1973) carried out the first test involving combined loads, the threaded rods used in the experiment instead of bolts for easier handling. Moreover, threaded rods are easy to clamp in a tension testing machine. At the first, the tension force was applied to a specific level of its own tension resistance, then a shear force was applied by a second machine, three plates were used to obtain a two shear plan situation. The test only dealt with a material strength of 4.6.

Later on, Knobloch, M. and Schmidt, H. (1987) conducted the second German test which involved a slightly bigger test series. Similar to the first test, the investigation performed on the round bar instead of bolts, but the difference was that unthreaded (plain) and threaded rod were tested under combined tension and shear loading. Threaded rod represented bolts with the shear plane passing through the thread and the plain rod represented bolts with the shear plane passing through the shank. The material strengths, which tested in this investigation, were for 4.6, 5.6, 8.8, and 10.9, it was planned to test rods of strength 5.6 and 10.9 for the threaded rod but they did not fulfil the requirements for their strength. The 5.6 rods were not ductile enough, while the 10.9 material fell below the promised strength.

The results of all tests confirmed that there is a kind of quadratic correlation between shear load and tension loads. The experimental resistance of tension and shear for the rods are obtained, and then those values are divided by the pure tension and pure shear strength of the basic material. Figure 2.12 illustrates test points which are relatively grouped around the quadratic curve, the vertical axis represents normalised tension and the horizontal axis represents normalised shear. Based on that, Knobloch, M. and Schmidt, H. (1987) concluded that using a quadratic curve is reasonable. As a result of this in 1990 the quadratic as interaction rule was added to the German DIN 18800-1.



test on round bar



test on threaded rod

Figure 2-13 Test results (Knobloch and Schmidt 1987)

$$\left(\frac{F_t}{F_{td}}\right)^2 + \left(\frac{F_v}{F_{vd}}\right)^2 \leq 1.0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.5.2.5$$

Where

F_t , F_v is the tension and shear componets in the bolt respectively

F_{td} , F_{vd} are the design strength for a bolt under pure tension and pure shear respectively

2.5.4 Statistical evaluation of current design rules in EC3 and BS standard

The purpose of assembling the Eurocode is to provide design procedure for steel structures in the form of common unified rules. Regarding bolted connection, the process went through two stages, the first was to collect suggestions for which rules should be used for single verification, and the second was to compare suggested rules with the experimental data by conducting the statistical evaluation. Snijder, H. et al (1988) carried out a statistical evaluation of available test results so as to achieve strength functions and model factors for bolted connection.

As far as combined loadings on bolts are concerned, the statistical analysis was done based upon the data from two test series. One carried out in Manchester and another one in Delft both test series worked with bolts. In Manchester test, the investigation was carried out on black bolts with the grade of material 4.6 and with bolt diameter M20, its purpose of this test to ascertain the ultimate capacity of the bolt under different ratios of tension and shear loading. The bolts were tested in pairs under statically applied loads, both bolt elongation and slip between plates were recorded. The tests were separated into failure in the thread and in the shank. Regarding Delft test, this test covered much more parameters compared to Manchester test, bolts with the grade 4.6, 8.8. 10.9 and with the bolt diameters M12 and M20 were tested. Similar to Manchester test, the experiment was further distinguished between shear in the shank and in the thread. Table 2.4 summarises the parameters and the number of repeated tests in each angle, and then the evaluation chart is used for showing the experimental data in both Manchester and Delft in figures 2.13, 2.14, 2.15, and 2.16. It is important to say that EC3 only depends on these two tests to determine strength function for bolts under combined tension and shear loading, which shows Eurocode 3 has a weak background in deriving the interaction equations.

Table 2-3 Number of tests used for EC3 evaluation

Place of test	Bolt diameter	Bolt grade	No. of repeated test in each angle						
			0°	15°	30°	45°	60°	75°	90°
Manchester	M20	4.6	8	13	11	5	5	5	11
Delft									
	M12	4.6	9	*	7	*	6	*	10
	M20	4.6	13	2	4	4	8	8	12
	M12	8.8	8	2	4	2	8	2	6
	M20	8.8	10	2	5	2	5	3	8
	M12	10.9	6	2	2	2	6	2	6
	M20	10.9	8	*	2	2	8	2	4

- Both tests in Manchester and Delft are distinguished between shear plane in the shank and in the thread. Therefore, the number of repeated test should be divided by two for each angle.

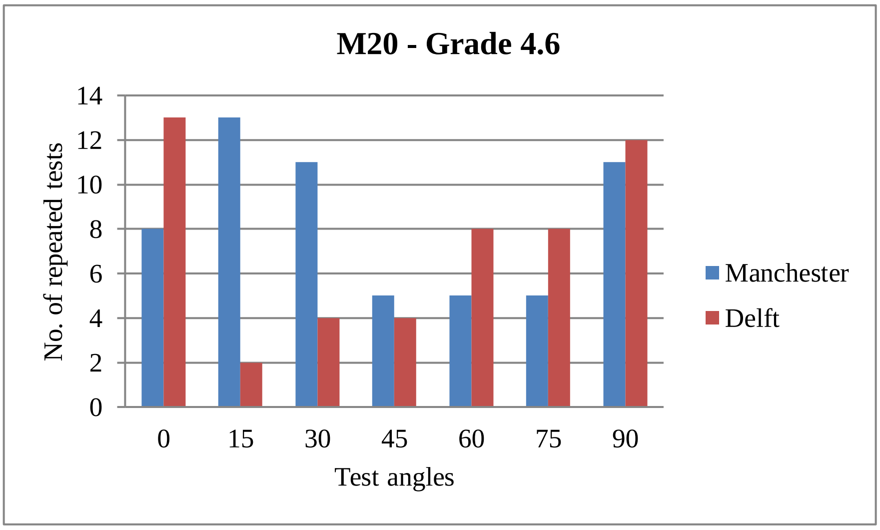


Figure 2-14 Variation in the number of repeated test

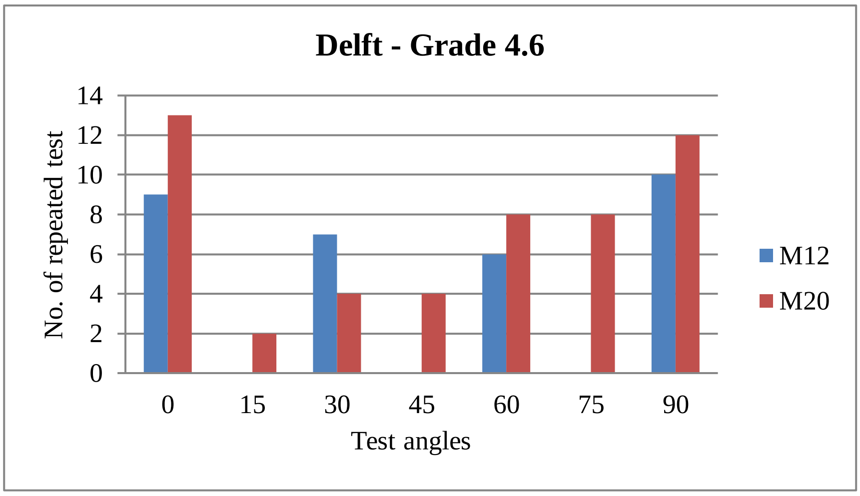


Figure 2-15 Number of test in the grade 4.6 Delft

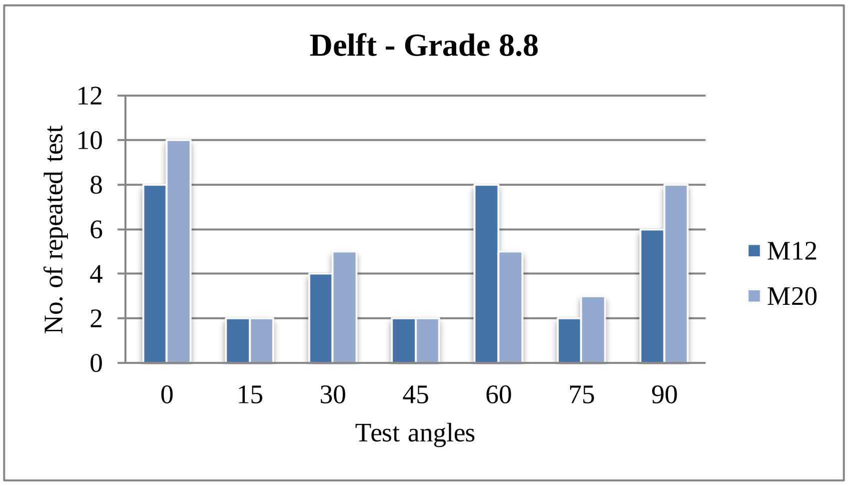


Figure 2-16 Number of tests in the grade 8.8 Delft

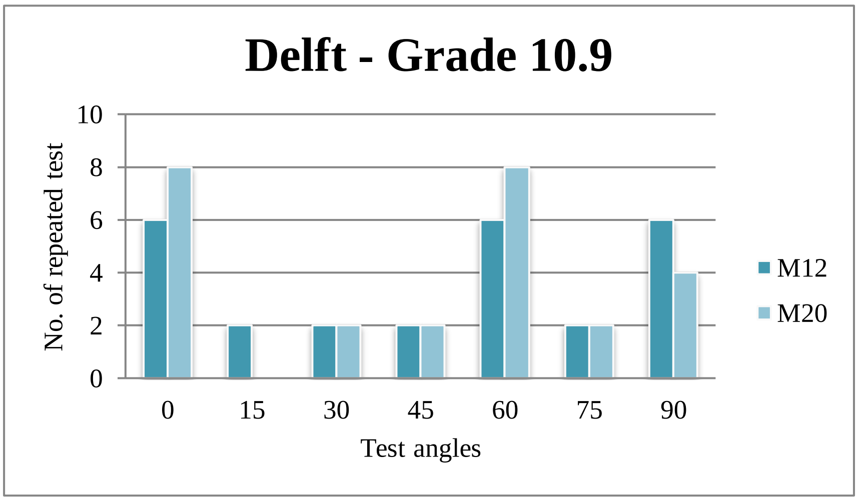
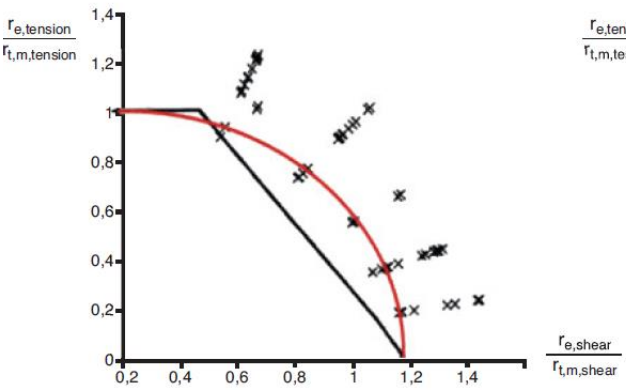


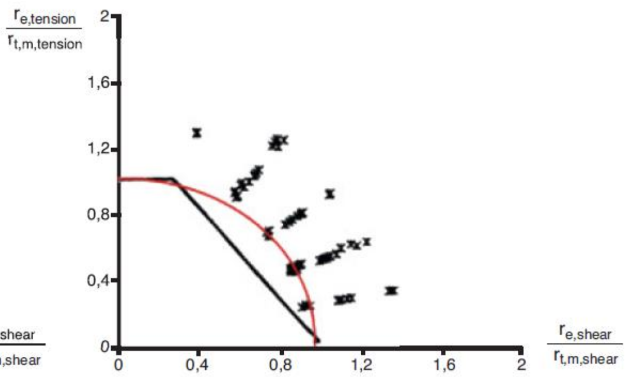
Figure 2-17 Number of tests in the grade 10.9 Delft

The arrangement of the test setups in Delft and Manchester were similar except in that in Manchester two bolts were tested in one instance whereas in Delft one bolt was tested in one instance. The arrangement was using a head-plate construction, which was pulled at different angles to apply the force. The bolts were tested in eight different angles which were 0° (pure tension), 15°, 30°, 45°, 60°, 75°, and 90° (pure shear). Selecting those test angles can be different depending on the drawing of interaction model, and choosing appropriate angles resulted in accurate interaction model. Renner A., and Lange J. (2012) tested the bolt on the same angles as shown previously except in that they changed angles 60° and 75° to 67.5° in the test series. Steeve, B. and Wingate R. (2012) conducted an experiment on the strength capability of aerospace threaded fastener under combined tension and shear loading, they used almost different angles for the test series which are 0° (pure tension), 22.5°, 45°, 67.5° and 90° (pure shear)°.

All results from Manchester and Delft tests were analysed together and resulted in the determination of the design rules for bolts under combined tension and shear in EC3. To draw the interaction model, the failure forces were separated for tension and shear components with respect to the angle which the bolts were testing, and were divided by the pure tension and pure shear strength of the basic material and then plotted on appropriate axes. Figure 2.17 shows the test data from Manchester and Delft experiment on bolts under combined loading, it can be seen drawing a quadratic curve on the graphs reveals that this function is apparently not in the safe side. As a result of that, EC3 came up with a new design rule which is a combination of both British standard and previous draft of EC3 in 1984.



Threaded in shear plane



shank in shear plane

Figure 2-18 Test evaluation overview for EC3 (Snijder, H. et al 1988)

Where

$r_{e,tension}$: tension component from experimental result.

$r_{tm,tension}$: theoritical tension resistance of the bolt obtained by strength function.

$r_{e,shear}$: shear component from experimental result.

$r_{tm,shear}$: theoritical shear resistance of the bolt obtained by strength function

There were two different cases in the statistical evaluation of bolts under combined tension and shear loading. The first one was if the shear plane passes through the threaded portion of the bolt, and the second one was if the shear passes through the shank of the bolt. Snijder, H. et al (1988) state that in the former the failure will most likely to occur over the threaded area while in the latter the failure may either take place in the shank or the threaded part. These two resulted in two miscellaneous equations for design as shown below for combined loading on bolts.

If shear plane passes through the threaded portion

$$\frac{F_t}{1.4\ F_{td}} + \frac{F_v}{F_{vd}} \leq 1.0 \quad \text{2.5.2.6a}$$

$$\frac{F_t}{F_{td}} \leq 1.0 \quad \text{2.5.2.6b}$$

If shear plane passes through the shank

$$\frac{F_t}{1.8\ F_{td}} + \frac{F_v}{F_{vd}} \leq 1.0 \quad \text{2.5.2.7a}$$

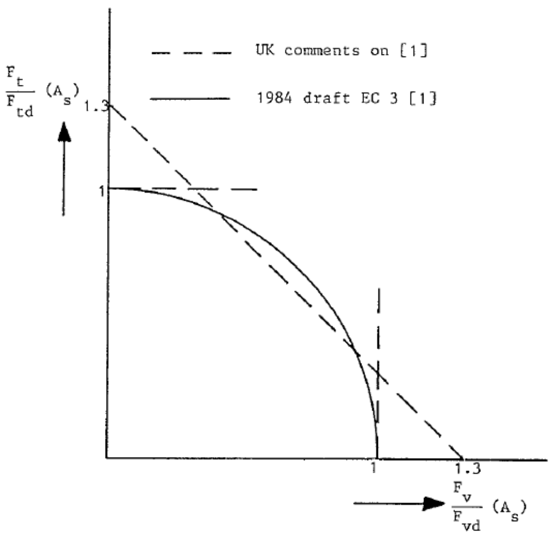
$$\frac{F_t}{F_{td}} \leq 1.0 \quad \text{2.5.2.7b}$$

However, so as to obtain an equation with the same coefficients as in the equation for combined tension and shear in the thread, equation 2.5.2.7 may be changed to 2.5.2.6. Which in turn, results in a unified equation for combined loading and the design calculation will be easier. But it should be noted that equation 2.5.2.6 is conservative when compared to equation 2.5.2.7. Thus, EC3 provides an individual equation for bolts under combined tension and shear which is

$$\frac{F_t}{1.4\ F_{td}} + \frac{F_v}{F_{vd}} \leq 1.0 \quad \text{2.5.2.8a}$$

$$\frac{F_t}{F_{td}} \leq 1.0 \quad \text{2.5.2.8b}$$

The above equation was derived based upon failure mechanism of bolts under combined loading when the shear plane passes through the threaded portion. Figure 2.18 shows an interaction model for both EC3 and BS, single



tensile failure mechanism is on the vertical axis and single shear failure mechanism is on the horizontal axis. Up until the statistical evaluation, there were two kind of interaction model, circular interaction (EC3 draft 1984) and tri-linear design function (UK comments).

Figure 2-19 Interaction of shear and tension in the threaded of bolts

In the EC3 draft 1984, the design function for the bolt failure under combined loading has been presented as follows

$$\text{Design strenght of bolt under combined tension and shear } (F_{id}) = \frac{f_{ub}\, A_s}{\gamma_m} = 0.8\, f_{ub}\, A_s$$

Referring to equation 2.4.2.1: $F_{id} = F_{td}$

Where

$$\text{Strength of bolt under combined tension and shear } (F_i) = \sqrt{(F_t)^2 + 2.(F_v)^2}$$

The value of f_i should not be greater than f_{id}

The requirement can now be written as follows:

$$F_i \leq F_{id}$$

Then substitute

$$\sqrt{(F_t)^2 + 2.(F_v)^2} \leq F_{td}$$

$$\left(\frac{F_t}{F_{td}}\right)^2 + 2.\left(\frac{F_v}{F_{td}}\right)^2 \leq 1.0$$

The relation between F_{td} and F_{vd} is

$$F_{td} = 0.8\, f_{ub}\, A_s$$

$$F_{vd} = \frac{0.8\, f_{ub}\, A_s}{\sqrt{2}}$$

Comparing these two equation resulted in

$$F_{vd} = \frac{F_{td}}{\sqrt{2}}$$

Using this relation in the requirement for combined tension and shear loading results in the circular interaction design equation:

$$\left(\frac{F_t}{F_{td}}\right)^2 + \left(\frac{F_v}{F_{vd}}\right)^2 \leq 1.0 \quad \ldots\ldots\ldots\ldots 2.5.2.9$$

In the evaluation, Snijder, H. et al (1988) decided to take the tri-linear design model into consideration in the statistical evaluation for some reasons. Firstly, tri-linear interaction equation is easy for use in hand calculations. Secondly, the tri-linear approach suggests that for the situation where bolts are subjected to either shear or tension associated with a small contribution from the other effects, this secondary effect can be neglected. Finally, the UK comments suggests that there is no reduction in tensile capacity for small value of shear and vice versa, whereas when both tension and shear are at about 70% of their individual capacities the circle interaction formula tends to overestimate the bolt capacity. The following shows the suggested tri-linear design equation in the UK comments

$$\frac{F_t}{F_{td}} \leq 1.0 \quad \ldots\ldots \quad 2.5.2.10a$$

$$\frac{F_t}{F_{td}} + \frac{F_v}{F_{vd}} \leq 1.3 \quad \ldots\ldots \quad 2.5.2.10b$$

$$\frac{F_v}{F_{vd}} \leq 1.0 \quad \ldots\ldots \quad 2.5.2.10c$$

Statistical evaluation was carried out to compare equation 2.5.2.9 and equations 2.5.2.10; it was observed that the quality of both equations seems to be about equal. Since the equations 2.5.2.10 are easier to use, these equations are adopted. Having adopted equations 2.5.2.10, based upon the statistical analysis concluded that the adopted equation should be modified for

$$\frac{F_t}{F_{td}} \leq 1.0 \quad \ldots\ldots \quad 2.5.2.11a$$

$$\frac{F_t}{1.4\ F_{td}} + \frac{F_v}{F_{vd}} \leq 1.0 \quad \ldots\ldots \quad 2.5.2.11b$$

Where

F_t , F_v is the tension and shear componets in the bolt respectively

F_{td} , F_{vd} are the design strength for a bolt under pure tension and pure shear respectively

Renner, A. and Lange, J. (2012) indicate that the current standard rules have a weak background because they have based on a few experimental data whereas they are comprehensive. Moreover, as stated before, most of the existing tests do not represent what really happens in the bolt itself under combined loading. Therefore, these two authors started their own test series that is to close the gap that exists in the area of combined shear and tension ratio on bolts. The author's summary based on previous investigation was that resistance of bolts might be affected by the ductility of the specimen therefore they conducted the real bolt instead of using bars and threaded rod as before. Furthermore, the influence of the shear plane position was taken into account so as to determine whether it is appropriate to treat both situations the same way.

In the experiment, the total 67 bolts were tested for grades 4.6, 8.8 and 10.9 with different position of shear plane. Table 2.5 summarises the tests conducted in this experiment, in most of the angles only three bolts were tested which shows that current standard rules can be evaluated by this number.

Table 2-4 Test results

	Bolt diameter	Bolt grade	No. of repeated test						
			Tension 0°	15°	30°	45°	67.5°	Shear 90°	2 shear planes
Threaded in shear plane	M20	4.6	4	3	3	3	3	4	4
	M20	8.8	3	3	3	3	3	3	3
Shank in shear plane	M20	4.6	*	*	*	*	*	*	*
	M20	10.9	4	3	3	3	3	3	3

Renner, A. and Lange, J. (2012) concluded that the current interaction rules for combined tension and shear in Eurocode 3 for bolts is far conservative that is because it is based on rather weak assumptions and few test results, and the real stress situation in the bolts has never been considered. In addition, it is observed that quadratic model might not be on the safe side. Therefore, they suggested for further tests and finite element analysis so as to be able to give a conclusive assertion.

2.5.5 Review an experiment on blind bolts resistance.

With regard to combined tension and shear on blind bolts which is a novel type of connection to steel hollow sections, the principle and design rules might not involve significant differences. Since, SCI Steel Knowledge (2009) has carried out a series of tests for M10 and M20 for three different angles which are 30°, 45° and 60° so as to verify the capacity of blind bolts. It was observed that most of failures occurred in tension not in combined mechanism and concluded that tension and shear interact in the shank length of the bolt. Figure 2.20 shows the blind bolt that was tested at the University of Manchester.

Figure 2-20 Blind bolts

In the SCI report (2009) In order to validate the current rules for blind bolt, the mean value of tension and shear used to plot on the interaction curve. As it is shown in Figure 2.21 all test results are outside of the design region which is set for combined tension and shear in British standard and Euro code. However, the SCI report (2009) believes that there is no reason for not using current design rules for blind bolt.

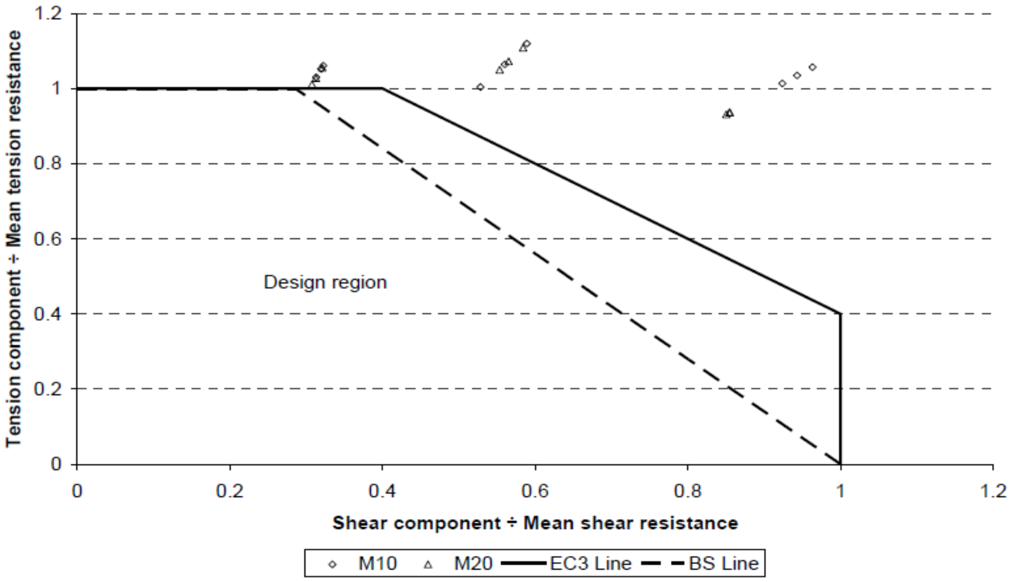


Figure 2-21 Test results on interaction of combined tension and shear (SCI 2009)

As a result, the same design rules for combined tension and shear are suggested for blind bolt based on BS EN 1993-1-8 and BS 5950-1 as follows. However, beside the equation for combined tension and shear, bolts should satisfy separate equations for both tension and shear.

BS EN 1993-1-8

$$\frac{F_t}{1.4\,F_{td}} + \frac{F_v}{F_{vd}} \leq 1.0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2.5.3.1$$

Where

F_t , F_v is the tension and shear componets in the bolt respectively

F_{td} , F_{vd} are the design strength for a bolt under pure tension and pure shear respectively

BS 5950-1:2000

$$\frac{F_t}{P_t} + \frac{F_v}{P_s} \leq 1.4 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2.5.3.2$$

Where

F_t , F_v is the tension and shear componets in the bolt respectively

F_{td} , F_{vd} are the design strength for a bolt under pure tension and pure shear respectively (check BS standard)

The point that should be taken into account in the SCI report is that all tests are focused on the strength of the blind bolt under various shear components in the combination of loads. This can be seen in table 2.6 that tension loads are changed slightly compare to shear forces. However, it was stated that actual strength of bolts might be affected by changing tension and shear ratio, and location of shear plane. Also, Chesson, Faustino, and Munse (1964) believe that maximum strength of bolts may be indicated when tension is dominant.

Table 2-5 Test results of combined tension and shear (SCI 2009)

Angle of testing Ø		M10			M20		
		Maximum Force (F) kN	Tension* kN	Shear* kN	Maximum force (F) kN	Tension kN	Shear kN
Pure tension 0°		18.63	18.63	0.0	80.41	80.41	0.0
		19.73	19.73	0.0	81.19	81.19	0.0
		**	**	0.0	84.00	84.00	0.0
		18.26	18.26	0.0	81.38	81.38	0.0
		18.11	18.11	0.0	85.53	85.53	0.0
30°		22.88	19.82	11.44	100.53	87.06	50.27
		22.70	19.66	11.35	97.88	84.77	48.94
		22.22	19.24	11.11	96.32	83.42	48.16
45°		26.53	18.76	18.76	125.11	88.46	88.46
		29.57	20.91	20.91	122.53	86.64	86.64
		28.12	19.88	19.88	129.31	91.44	91.44
60°		38.66	19.33	33.48	154.42	77.21	133.73
		39.48	19.74	34.19	154.53	77.27	133.83
		37.86	18.93	32.78	153.68	76.84	133.09
Pure shear 90°	Slotted region	40.25	0.0	40.25	157.49	0.0	157.49
		33.77	0.0	33.77	150.91	0.0	150.91
		32.45	0.0	32.45	161.16	0.0	161.16
	Threaded region	58.90	0.0	58.90	n/a***	n/a	n/a
		58.35	0.0	58.35	n/a	n/a	n/a
		58.16	0.0	58.16	n/a	n/a	n/a

*The tension component is calculated as FcosØ, and the shear component as FsinØ.

**Test failed

***Not tested in threaded region

It can be concluded that there are limited information about behaviour of blind bolts under combined tension and shear, up to date only those results are available for blind bolt. However, nowadays various types of blind bolt exist which might be difficult to apply these rules because they have used in different configurations.

2.6 Concluding Remarks

- Structural steel joint is a complex zone. Therefore, it needs a well understanding in terms of classification, sorts of connection and behaviour of individual components. On the other hand, lack of information has limited a well understanding of the behaviour of the whole joint. Regarding the blind bolt connection, the bolt itself needs more investigation to understand the overall response of the connection.

- Blind bolted connection is so far a leading alternative to connect open and hollow section. Therefore, many types of blind bolt appeared and investigated to understand the behaviour of the bolt such as Lindapter hollo-bolt. The HB is apparent because of commercial availability and easy installation in site whereas investigations observed that this bolt has low strength and stiffness in connection and it is weak under direct force (pure tension).

- EHB is a newly modified of standard HB. Stiffness and strength of EHB connection to concrete filled hollow section has improved compare to the standard HB. Speaking generally, among the blind bolts EHB is the one that can achieve moment resisting connection. However, the performance of EHB remains to be seen in further investigation because it is a novel type of bolt.

- Behaviour of bolts under combined tension and shear is complex in terms of controlling position of shear plane and the ratio of tension and shear which influence on failure mode. The current specifications for design of bolt under combined loading are different, each of DIN, BS and EC3 has its own interaction equation. However, they are not based on strong background information because few tests were carried out in that area. Based on the past investigation on blind bolt, it was concluded that design rules for standard bolt can apply to the blind bolt.

This review can give direction for further investigation in the area of blind bolted connection especially Extended Hollobolt connection because of the novelty of this bolt. On the whole, it is recommended to investigate in EHB strength under combined tension and shear.

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