BEHAVIOUR OF AXIALLY LOADED STRUCTURAL BOLTING ASSEMBLIES IN FIRE

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Abstract
Bolt assemblies used in structural connections may fail in tension via two modes: Necking, which is a ductile failure, and thread stripping, which is a brittle failure mechanism. During a fire, a ductile failure mode is preferable as it provides continued load transfer from beams to columns for the longest amount of time, allowing for building evacuation. Bolt assemblies have been tested under tension at a range of strain rates and temperatures to observe both failure modes. Tests showed that those bolts with a non-martensitic microstructure failed in a beneficial ductile manner, contrary to the current standards.

Keywords: Bolt assemblies, ductile and brittle failure, microstructure

INTRODUCTION

The robustness of connections, and therefore bolt assemblies, is essential for the transfer of loads from beams to columns to avoid progressive collapse. Two failure modes exist under tension; shank necking (breakage) and thread stripping. The latter involves heavy thread deformation causing the nut to pull off the end of the bolt shank. This is a relatively brittle failure compared with shank breakage, and according to published work tends to occur at lower forces. During fire it is essential for bolt assemblies to have sufficient ductility to accommodate thermal expansion and subsequent contraction of adjoining members. Thread stripping should therefore be avoided. This paper investigates the factors which influence the failure mode at elevated temperatures through microstructural characterisation, tensile testing and finite element modelling.

1   BEHAVIOUR OF NUTS AND BOLTS UNDER FIRE CONDITIONS

Strength reduction factors prescribed by Eurocode 3 (BSEN1993-1-2 2005) are currently applied to fasteners in structural fire design. These are based on the temperature-dependent strength of steel, and take into account thread deformation or the bolt failure mode. A simplistic assumption is that failure mode depends on thread engagement length and the relative strengths of the mating threads. When the thread engagement length is long and mating thread strengths are comparable, bolt breakage is most likely. When the strength of one thread set is greater than the other and the length of thread engagement is short, thread stripping will occur in the weaker thread set. A detailed model exists for the prediction of failure mode at ambient temperature (Alexander 1977, Ref. No 770420), but as yet no assumptions have been made about the strain rate or temperature dependency of the failure mode.

A number of bolt assembly tests have previously been carried out at elevated temperature under steady-state conditions to evaluate and compare the performance of different bolt assemblies in fire (Kirby 1995; Hu, Davison et al. 2007; Gonzalez and Lange 2009; Gonzalez 2011). These have been carried out on assemblies of different geometrical tolerances; the tighter tolerance, 6g6AZ, as specified in (BSEN14399-4 2005) and (BSENISO10684 2004), and the looser tolerance, 8g7H, for bolts specified to (BS4190 1967; BS4190 2001). The studies also contain different diameters, steel grades, forming methods (hot and cold) and finishes, as detailed in Tab. 1. The test methods employed by the different authors, and their

resultant ultimate tensile capacities and failure modes, are shown in Tab. 2. Some assemblies failed by a single failure mode, while some failed by a combination (where N = necking, S = thread stripping and C = combination).

Normalising the ultimate load capacities of bolt assemblies tested at elevated temperature to those at ambient provides strength reduction factors which can be compared to those used in fire engineering design (BSEN1993-1-2 2005). The traditionally conservative Eurocodes surprisingly suggest reduction factors less severe than those observed in some bolt assemblies at all temperatures, but most significantly at temperatures greater than 300 °C. This may be attributable to the reduced strength in the threads causing greater thread deformation at higher temperatures and potentially a different tempering (softening) behaviour of the bolt material compared to the steel used to create the strength reduction factors available in Eurocode 3.

Tab. 1: Summary of the processing and geometrical tolerances of bolt assemblies tested at elevated temperatures in previously published work

Author		Assembly			Bolt				Nut			
	Ref.	d (mm)	Tolerance	Code	Grade	Formed	Finish	Code	Property Class	Formed	Finish
Kirby	1	20	8g7H	4190	8.8	CF	SC	4190	8	HF	SC
	2	20	8g7H	4190	8.8	CF	SC	4190	8	CF	G
	3	20	8g7H	4190	8.8	CF	SC	4190	8	HF	SC
	4	20	8g7H	4190	8.8	CF	SC	4190	8	CF	G
	5	20	8g7H	4190	8.8	HF	SC	4190	8	HF	SC
Gonzalez	6	16	6g6AZ	14399-4	10.9	CF	G	14399-4	10	-	G
	7	16	6g6AZ	14399-4	10.9	CF	G	14399-4	10	-	G
Hu	8	20	-	4190	8.8	-	-	-	10	-	-
	9	20	-	ISO 4014	8.8	-	-	-	10	-	-

Where CF = cold formed, HF = hot formed, SC = self-colour and G = hot dip galvanised

Tab. 2: Summary of the ultimate load capacities obtained from steady-state tensile tests at a range of temperatures in previously published work

Ref.	Strain rate (min^{-1})	Heating rate (°C/min)	Holding time (min)	F_u (kN) at Temperature (°C)										Failure mode
				20	100	150	200	300	400	500	550	600	700	
1				226	216	-	215	217	178	126	94	59	24	N
2				198	191	-	177	190	168	118	86	54	23	S
3	0.001-0.003	5-10	15	206	201	-	206	203	168	122	96	62	27	N
4				189	180	-	168	176	158	112	85	54	25	S
5				232	217	-	215	206	183	144	116	80	28	C
6	0.001-0.005	-	30	266	-	-	254	252	210	123	78	47	19	C
7				264	-	-	256	245	203	121	76	50	18	C
8	0.0001*	2-2.5	15	202	-	198	-	187	140	75	-	39	-	N
9				239	-	232	-	225	168	115	-	48	-	N

* Assuming a 30 mm gauge length

The general trend observed was for necking failures to occur at higher ultimate tensile strengths than stripping failures for 8.8 bolts, while the 10.9 bolts failed at higher ultimate load capacities by a combination of thread stripping, necking and liquid metal embrittlement. Assemblies 6 and 7 were temperature-dependent, so that a combination of necking and thread stripping occurred up to 420°C, liquid metal embrittlement from 420-650°C and pure

stripping above 650°C. Assembly 5 failed by a combination of necking and thread stripping at all temperatures, with both failure modes occurring at similar ultimate load capacities.

2   UNIAXIAL TENSILE TESTING

A series of uniaxial tensile tests carried out on turned-down bolts, chosen to eliminate the effects of thread deformation, have been carried out to provide realistic material behaviour to use in a finite element model developed in ABAQUS, using the material properties defined in ISO 898-1, 898-2 and the reduction factors from Eurocode 3. The bolt head is removed and the shank turned-down to a diameter of 7 mm for a parallel length of 35 mm with a 6 mm radius at each end. True thread geometries measured from a number of bolt assemblies from the same batch are included in a pre-existing finite element model. The model will be validated by tensile tests, carried out on bolt assemblies from the same batch as the turned down bolts, at the same temperature and strain rate combinations.

The assembly chosen for this study is typical of that used in UK construction, consisting of a Grade 8.8 galvanised bolt and Property Class 10 galvanised nut to the tighter geometrical tolerance of 6g6AZ. All bolt material and bolt assembly tests were carried out on a single batch from a single manufacturer, to ensure consistent results.

2.1 Test setup

The apparatus includes a convection furnace and the same tools used by (Hu, Davison et al. 2007) as can be seen in Fig. 1. Since the test apparatus was designed for tensile testing of bolt assemblies two internally threaded extensions were machined which could accommodate a short M20 bolt at one end and an M20 stub and nut at the other, with the turned-down bolt test piece in-between, as seen in Fig. 2. For both bolt assembly and turned-down bolt tests a tensile force is applied by the top grip to the bottom face of the nut whilst the bottom grip remains stationary.
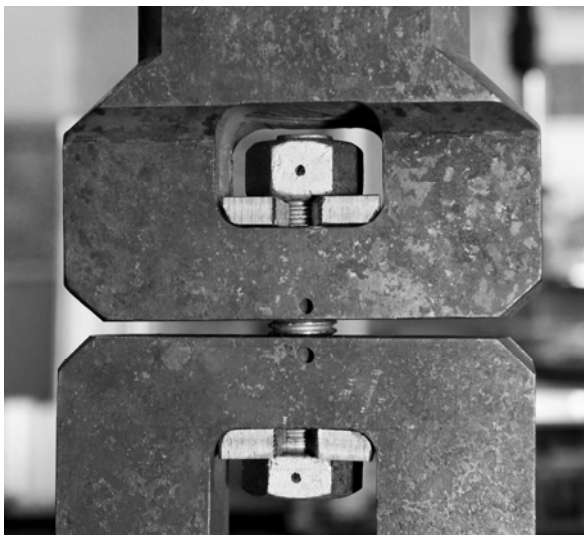

Fig. 1 ESH testing equipment used for turned-down bolt and bolt assembly testing.

Fig. 2 Test setup for turned-down bolt specimen.

Temperature is measured by a thermocouple placed in the bottom shoulder of the turned-down bolts and the centre of the bolt head in the bolt assembly tests. Elongation is calculated by digital image correlation using a Canon EOS 1100D camera with an EFS 18-55mm lens and an automatic trigger system connected to the LabVIEW module. This allows data to be written to file at the same time as the trigger is activated, to allow strain calculation up to failure. Both ends of the gauge length are marked with glass beads attached to the surface of

the specimen with fire cement, so that they are visible in profile without being detrimental to strength.

Based on the test methods used in previous bolt assembly tests it was decided that a study into the failure behaviour of bolt assemblies and bolt material should include a range of temperatures up to 700°C and strain rates ranging from 0.002 min^{-1} up to 0.02 min^{-1}. The slowest of these is comparable to the strain rates used by (Kirby 1995) and the maximum strain rate at the mid-span of a simply supported beam subjected to an evenly distributed load when calculated on the basis of a limiting deflection of L^2/9000d (mm/min) (BS476-20 1987). Strain rates of 0.01 and 0.02 min^{-1} have also been chosen to reflect the high strain rates experienced during plastic deformation. Unlike the tests shown in Tab. 1 the strain rate is maintained to failure rather than increased beyond 2 – 5 % proof stress, in order to reduce test times. Temperatures set at ambient, 550°C, 620°C and 700°C were chosen, since 550°C is commonly assumed to be the critical or limiting temperature above which steel retains 60% of its ambient-temperature strength and 700°C is a realistic temperature for unprotected connections to reach during a building fire.

2.2 Bolt Material Results

The first three tests, carried out at 0.002, 0.01 and 0.02 min^{-1} at ambient temperature gave some surprising results, as shown in Fig. 3, exhibiting behaviour characteristic of three different microstructures; pearlite, bainite and martensite. The yield plateau is characteristic of pearlite, but not the martensite that quenched-and-tempered M20 grade 8.8 bolts should contain (90% martensite at their centres, as specified in (BSENISO898-1 2009)). Since all three bolts were from the same batch it can be assumed that they have the same chemical composition, which is within the limits of (BSENISO898-1 2009), and therefore the difference in microstructure is attribuTab. to the cooling rate during quenching. A faster cooling rate leads to transformation from austenite (present at temperatures above around 730°C) to a harder, more brittle, martensite phase, while slower cooling allows for diffusion of carbon atoms and transformation to bainite and pearlite. Hardness readings taken at the bolt neutral axes of the three specimens confirms the presence of different microstructures, with those of the two weaker materials lying below the minimum limit of ISO 898-1.
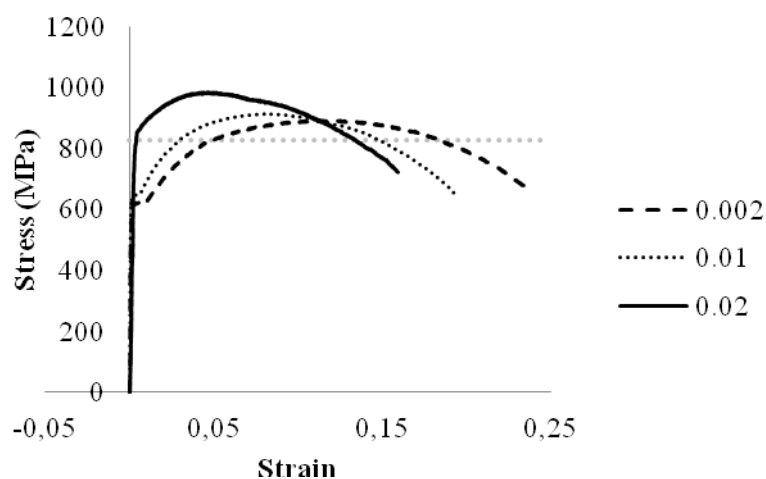

Fig. 3 Ambient-temperature stress-strain curves for 0.002, 0.01 and 0.02 min^{-1} showing behaviour characteristic of pearlite, bainite and martensite respectively.

Vickers hardness tests were carried out on the underside of the bolt heads prior to machining test pieces, to ensure that all subsequent specimens contained pearlite to provide worst-case material properties for the finite element model. The repeated test results shown in Fig. 4 exhibit negligible effects of strain-rate on stress; the results were therefore averaged for the three strain rates. At elevated temperatures the strain-rate effect is significant, as shown in

Fig. 5. These results can be simplified to multi-linear curves for input to the finite element model. The resultant strength reduction factors from these tests show that higher strain rates tend to lead to higher reduction factors (less of a reduction in strength) than those from lower strain rates. Most values, however, also fall below those specified in Eurocode 3.
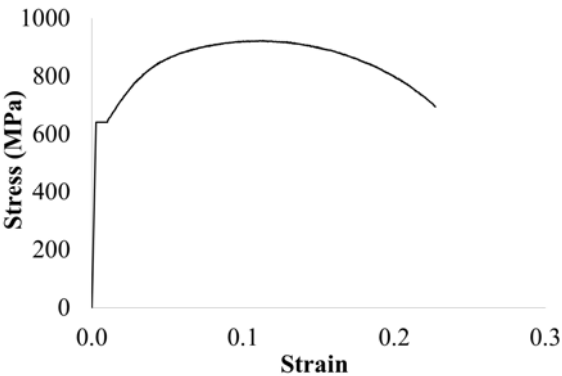

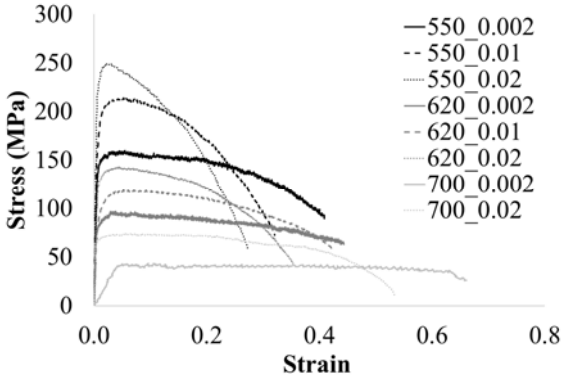Fig. 4 Average ambient temperature stress-strain curve for turned-down bolts.

Fig. 5 Elevated temperature stress-strain curves for turned-down bolts.

2.3 Bolt Assembly Results

Force is plotted against elongation, measured from the top face of the nut to the bottom face of the bolt head, as shown in Fig. 6.
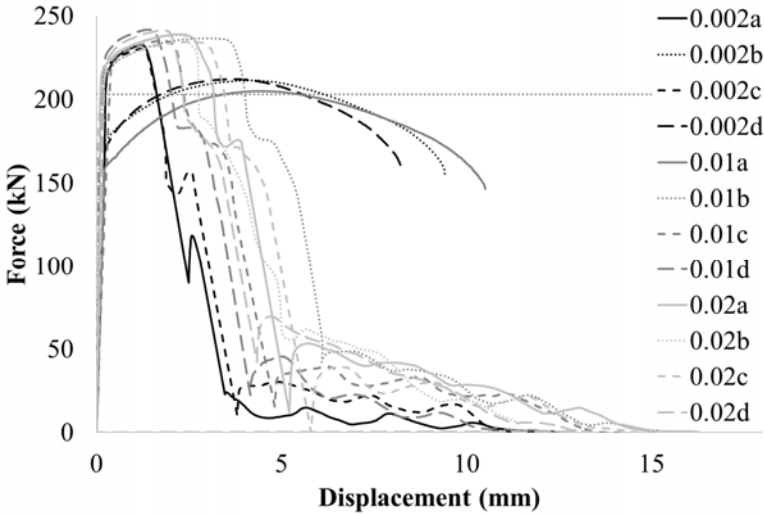

Fig. 6 Ambient-temperature force-displacement curves for bolt assemblies at strain rates 0.002, 0.01 and 0.02 min^{-1}.

Those assemblies which failed due to thread stripping did so at significantly higher loads than those which failed due to necking, with both failure modes having little strain-rate effect. Hardness testing of the undersides of the bolt heads of the failed specimens shows that those which failed due to necking have lower hardness, so pearlitic or bainitic microstructures can be inferred. All bolt assemblies tested failed above the minimum ultimate tensile load of 203kN prescribed in ISO 898-1. The assemblies that failed through necking did so at significantly lower loads than those which failed through thread stripping, but exhibited ductile failures - bolt assemblies must be ductile in order to continue to transfer loads

effectively from beams to columns during thermal expansion and subsequent sagging of beams during fire.

3   SUMMARY AND ACKNOWLEDGEMENT

Despite the lower ultimate load capacities observed in bolt assemblies which failed due to necking, it is still the preferred mode of failure during fire. Tensile testing carried out on bolt assemblies from the same batch has highlighted the importance of tight control during manufacture to ensure consistent material and mechanical properties. Interestingly, the desirable ductile failure mode occurred in bolts which contained a pearlitic or bainitic microstructure, as opposed to the tempered martensite specified. If ductility is essential to ensure structural robustness during fire, it is not apparent why the current objective is to aim for the strong, brittle starting microstructure of tempered martensite. The turned-down bolt test results will provide good material property data as input to finite element models.

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