

SUSCEPTIBILITY OF UNPROTECTED STEEL BOLTED CONNECTIONS TO EMBRITTELEMENT AFTER A FIRE

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ABSTRACT

Steel bolts (M20) subjected to heat treatments that simulate different potential scenarios in a building exposed to fire have revealed the possibility of significant embrittlement. Bolts rapidly quenched from elevated temperatures (900°C) exhibit a brittle fracture under Izod impact testing, whereas as-received bolts and bolts allowed to cool slowly from the same temperatures, exhibit a ductile failure. It is suggested that this behaviour represents a possible hazard when combined with tensile stresses that are generated within steel structures on cooling from a fire.

INTRODUCTION

The reduction in properties of steel during a fire can result in the collapse of a structure. While steel structural beams are now routinely protected against fire exposure by the use of coatings such as intumescent paints, the bolted connections remain a source of possible structural weakness during a fire. This technical note examines the possibility that unprotected bolts may allow premature collapse during the fire and also after the fire following cooling of the structure.

BACKGROUND

The use of structural steel framework for buildings is subject to design restrictions imposed in order to meet the various fire regulations imposed across the world. Typically building regulations impose a fire rating requirement linked to the time in a standard fire environment over which the strength of the structure is maintained above a critical threshold value. Steel loses both strength and stiffness at elevated temperatures and in general the fire rating of a building or zone of a building may be limited by the time required in a fire to raise the temperature of the steel to such a point that the structure is weakened to an unacceptable degree.

The exact allowable temperature may vary from country to country. In Japan the fire testing of steel columns and beams is governed by JIS A 1304-1975 and an average allowable temperature for steel is set at 350°C. In the UK building regulations usually allow a maximum temperature of 450-500°C.

For many applications steelwork will be provided with thermal protection sometimes by encasing the structural members in concrete or masonry forms which may be precast structures or sprayed onto the steel (1). For steel framed buildings the usual method of protection is to supply the steel members pre-coated with an intumescent paint of sufficient thickness to provide a thermal barrier during a fire. This is a relatively straightforward industrial process which can be undertaken in a cost effective manner.

However, a practical problem exists when the steel is joined to other sections during assembly. Most steel frame structures are assembled using steel bolts and these bolts represent a potential point of weakness for the structure. In a fire, failure of the unprotected bolts could result in collapse of the structure before the steel structural members have reached the critical temperature specified in the various building codes.

Painting the bolts after assembly is a feasible option that is currently practised by most of the industry. However recent trends in health and safety legislation suggest that this may become either more costly or

possibly be impractical as the use of chemicals containing volatile organic solvent components are restricted on site. The industry has begun to consider the possibility of leaving steel bolts unprotected and to assume that the temperature during a fire will not rise to a sufficient level to cause the bolts to fail within the fire rating of the building itself. This approach could be given additional support if the industry adopted high strength fire resistant bolts of the form currently used in Japan, albeit in combination with additional fire protection. F10T Fire resistant steel bolts are commonly used in Japan as the temperature required to reduce the strength and stiffness to unacceptable levels is raised to 600°C (2).

A number of examinations of the aftermath of real fires and realistic controlled fire experiments have considered the role of connections, including bolted connections. During tests undertaken over a period of time by the Fire Research Station, now Building Research Establishment at Cardington, in conjunction with British Steel (now Corus) and other partners, an important observation was the evidence of very high stresses imposed at connections due to cooling stresses after the fire (3-4). This series of tests has led to a set of guidelines on design for fire (5) which has commented on the behaviour of bolted connections. The following two quotes both refer to observed failures where thermal stresses have been induced in structures during cooling after a full scale fire (5).

“During the heating phase of the tests, connections performed well, however some connections suffered partial failure during the cooling phase. This was because the beams are subject to large compressive stresses during the heating phase; these arise from restrained thermal expansion and thermally induced curvature. The restraints had the effect of causing plastic compressive deformation and, in some cases, local compressive instability. Both of these result in shortening of the beams. As the beam cools, the plastic strains cannot be recovered and the beams are therefore shorter than before the fire. The overall effect is similar to the ‘lack-of-fit’ problems with which engineers are familiar. The connections were thus subject to tensile forces, which in some instances led to some form of failure”

“After the test, investigation showed that many of the bolts in the fin-plate connections had sheared.. The bolts had only sheared on one side of the primary beam. In a similar manner to the fracturing of the plate in Test 1, the bolts sheared due to thermal contraction of the beam during cooling. The thermal contraction generated very high tensile forces, which were relieved once the bolts sheared in the fin –plate on one side of the primary beam.”

Evidence for the existence of high cooling stress at connections was also presented in the reports of the Broadgate fire in London (6). In some instance these stresses had result in fracture of the bolts. The following quote is from reference 6.

“In cleated connections, there was some deformation of bolt holes. In one end-plate connection, two of the bolts had fractured; in another, the plate had fractured down one side of the beam but the connection was still able to transfer shear. The main cause of deformation was thought to be due to the tensile forces induced during cooling”

The effects of thermal exposure due to fire on residual bolt properties is not that significant if the bolt is allowed to cool slowly after the fire test. Reports by Kirkby (7) have shown that the bolts are softened but the effect is not dramatic.

The fire tests on conventional bolts(7) and on high strength fire resistant bolts (1) allowed the bolts to cool slowly. However, steel bolts will be subject to the same range of metallurgical transformations as conventional structural steels, and it is possible that rapid cooling of the steel, for example from dousing due to fire hoses, could result in significant changes in microstructure and hence mechanical properties. This might introduce a further problem in the use of unprotected bolts which could exacerbate the hazards caused by deformation in the hot state during the fire.

To investigate this concern a small number of standard M20 bolts were subjected to a variety of heat treatments intended to simulate different cooling scenarios that might be encountered in a fire.

TEST PROGRAMME.

Standard zinc coated M20 bolts were supplied for the programme. In order to assess the effect of microstructural changes due to heat treatments induced in a fire, the bolts were subject to impact tests.

The impact test configuration used was a standard Izod test using a conventional 300J pendulum impact machine as shown schematically in figure 1. This allows a falling striker to impact a specimen clamped in a vice as illustrated in figure 2.

Figure 1 Schematic of pendulum impact test machine (reproduced from Callister).

Figure 2 Method of fixing standard Izod notched specimen in a vice.

In order for the bolts to be securely fastened in the Izod vice, the bolts were machined to a constant diameter of 20 mm long the length of the bolt which removed the screw threads. The screw threads are a possible source of stress concentrations during an impact test and in order to ensure that the effect of the threads was taken into consideration, a single groove of a similar profile to the screw thread was machined around each bolt.

The machining also had the effect of removing the zinc plating on the bolts. This machined groove was used in place of the standard notch which is normally specified in a square cross section, Izod specimen, figure 2.

The bolts were then subjected to heat treatment by heating to 900°C in a furnace and leaving for one hour before allowing cooling in air (normalised) or being quenched in water.

The bolts subjected to the different heat treatments and cooling regimes were then impacted by a pendulum with 300J kinetic energy. An as-received (machined) bolt was also tested as a comparator.

The “as-received” and normalised bolts could not be fractured in the test. The bolts exhibited gross plastic deformation and bent but did not break. However, the quenched steel bolt fractured, absorbing a total of 280J. The fracture corresponded to the plane defined by the machined groove, figure 3

Figure 3 Machined bolts after heat treatment and impact testing (from left to right: “as-received”, normalised and water quenched)

The fracture surface of the failed quenched bolt was rough and macroscopically flat, figure 4, suggesting brittle fracture. A closer examination of the surfaces using a scanning electron microscope showed evidence of micro-plasticity, figure 5.

Figure 4: Optical photograph of the fracture surface of a quenched bolt. View area is approximately 8 mm in width.

Figure 5 ; Scanning electron micrograph of the fracture surface of a quenched specimen at high magnification. The surface show evidence of limited plastic deformation.

DISCUSSION.

The rapid water quenching of the steel bolt was intended to simulate the effect of a fireman's hose on the bolts and represent an extreme case of fire exposure induced heat treatment. It would appear that this form of treatment has dramatically reduced the impact properties of the bolts and facilitated a macroscopically brittle fracture. Slow cooling does not radically change the impact properties of the bolts.

The evidence of microplasticity as seen by the dimples and small areas of cavitation on the fracture surfaces suggests that the quenched steel did not transform fully into a martensitic structure but is likely to have a combination of different phases incorporating bainitic structures with the possibility of some martensite at the outer surfaces.

It is clear that steel bolts with this microstructure would be far more likely to fail when a steel structure was recovering from a fire in the cooling phase, than unexposed or slow cooled bolts. Furthermore, if the bolts were embrittled, any failure of structure above the embrittled connections that resulted in material falling onto the structure held in place by these connections could result in a secondary failure. This could in turn lead to a cascade effect with dramatic consequences and must be regarded as a hazard for teams working to repair or clear fire damaged buildings.

The steels used for standard M20 bolts in the UK have a relatively low hardenability. The fire resistant steels used in Japan have a much higher hardenability due to alloying which allows the bolts to achieve much higher strengths in the first instance. These steels would be much more susceptible to embrittlement during rapid quenching. This suggests that while the use of unprotected fire resistant steels might provide some benefits during the fire itself, they would result in enhanced safety concerns after the fire in the cooled building.

The studies of steel bolts in the literature have all concentrated on the performance of bolts at high temperature and the residual properties after slow cooling. This work has shown that although the bolts themselves are not seriously affected by slow cooling from a fire, failures can occur in bolted connections even if these connections have been protected during the fire itself. The possibility of inducing rapid cooling in unprotected bolts increases the risk of failure in such systems during the cooling phase.

CONCLUSIONS

Unprotected steel bolted connections would tend to introduce hazards in fire due to a combination of two factors:

- 1) They can significantly weaken during the fire itself leading to a possible failure of the connection and collapse of the structure.
- 2) If they survive the fire itself they may also fail during the cooling phase. If they have been subjected to rapid cooling (e.g. due to hosing with water) then they may be embrittled and fail as a result of induced tensile stresses generated within the cooling steel framework or as a result of falling debris.

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