Report No.	SL/HED/R/S1792/1/92/D
Date	15 May 1992
Classification	CONFIDENTIAL

Restricted to limited groups of British Steel staff

The Behaviour of High Strength Grade 8.8 Bolts in Fire

Swinden Laboratories
Moorgate
Rotherham, S60 3AR
Telephone: (0709) 820166
Telex: 547279
Telefax: (0709) 825337

British Steel Technical
A division of British Steel plc

BRITISH STEEL TECHNICAL
Swinden Laboratories

SL/HED/R/S1792/1/92/D

15 May 1992
CONFIDENTIAL

SUMMARY

THE BEHAVIOUR OF HIGH STRENGTH 8.8 BOLTS IN FIRE

B.R. Kirby

The behaviour of high strength grade 8.8 bolts in fire has been investigated.

Full component tests on M20 size bolts in tension and double shear at temperatures up to 800°C, have shown the present guidelines for designing at the Fire Limit State - BS5950:Part 8 are for the most part, conservative and there is some justification for increasing the design capacity.

The tests in tension in combination with grade 8.8 nuts have highlighted the possible premature failure due to stripping of the threads. This mechanism was found to be controlled by the degree of fit between the two components. Practical measures are suggested to enable the full capacity of the bolts to be utilised.

Hot tensile tests were carried out using machined specimens from bolts produced by different manufacturing processes. These were found to exhibit similar values of 0.2% proof stress over the temperature region where the normal design stresses coincide with the onset of plastic deformation.

The influence of temperature on residual hardness has highlighted the sensitivity of high strength bolts to overheating. Use has been made of the metallurgical changes to develop a technique for identifying the maximum temperature bolts may have achieved in a fire. This information can assist in the investigation of fire damaged buildings.

KEYWORDS

26
Lab Reports
Bolts

+BS3692
Nuts
Fire Tests

British Steel Technical
Swinden Laboratories,
Moorgate,
Rotherham S60 3AR
Telephone : (0709) 820166
Telex : 547279
Telefax : (0709) 825337

Cover Pages : 1
Text Pages : 13
Figure Pages : 24

INITIAL CIRCULATION

EXTERNAL CIRCULATION

Mr M. Tiddy	-	Cooper & Turner Ltd. (Sheffield)
Dr R.M. Lawson	-	Steel Construction Institute
Mr G.M. Newman	-	Steel Construction Institute

BRITISH STEEL GENERAL STEELS

COMMERCIAL

Commercial Office - Welded Tubes

Mr M. Edwards
Mr E. Hole
Mr N. Yeomans

Commercial Office - Commercial Steels

Mr J. Dowling
Mr R. A. C. Latter
Mr J.T. Robinson
Mr P. Wright

British Steel Technical HQ

Dr R. Baker, Director Research & Development

Swinden Laboratories

Mr G. Banks
Dr D.J. Latham
Dr D. M. Martin
Mr D.E. Wainman
Laboratory Manager
Library

THE BEHAVIOUR OF HIGH STRENGTH GRADE 8.8 BOLTS IN FIRE

1. INTRODUCTION

High strength grade 8.8 structural engineering bolts[1] are widely used in the building industry and although they are generally intended for applications in normal ambient temperature environments, under accidental fire conditions, they may achieve high temperatures.

Little is known about the strength characteristics of bolts in fire, yet the behaviour of these components is of paramount importance in maintaining the integrity of steel frameworks. This gap in knowledge is highlighted in the recently published code of practice on fire limit state design, BS5950:Part 8[2]. At the time of drafting the standard, no suitable experimental data existed, consequently, the capacity of bolts at elevated temperatures was described as 80% of the strength reduction factor for structural steel which corresponds to 0.5% strain, Table 1. The purpose of this investigation has therefore been conducted to endorse the present guidelines and if necessary, provide the basis for a future revision by evaluating the behaviour of grade 8.8 bolts at elevated temperatures both as a material and single components, used in combination with grade 8.8 nuts.

The integrity of bolts after fire is also an area of concern often expressed by engineers involved in the reinstatement of fire damaged structures however, only limited data is presently available[3,4]. Information on post fire residual properties is extended, with details of an evaluation procedure specifically developed to assist in establishing the temperatures attained by bolts during the fire process.

2. COMPONENTS SUPPLIED

M20 nuts and bolts were used throughout the investigation having mechanical properties meeting the requirements of BS3692:Grade 8.8, Tables 2 and 3. This particular size was chosen as it features in several of the fire resistant design methods developed by British Steel such as shelf angle floor beams and moment resisting beam to column connections. Since grade 8.8 bolts for structural applications are generally used in clearance holes, then in keeping with common practice, the components were supplied to the more relaxed dimensional tolerances given in BS4190[5].

High strength grade 8.8 bolts are manufactured by either a hot or cold forging operation followed by a quench and temper heat treatment to develop the required mechanical properties. The choice of process route varies between manufacturers and is controlled by the chemical composition of the feedstock, the size range and demand for a particular bolt, all of which are a function of producing a competitively priced product. It is therefore inevitable, that while the bolts will meet the specification for their intended use at ambient temperatures, their performance both during and after a fire will vary depending upon how they have been manufactured.

In the test programme three sets of bolts were supplied. To provide a consistent basis for establishing their behaviour under fire, within each set the bolts were manufactured in a single production run, using the same bar feedstock, forging operation and subsequent heat treatment conditions.

Bolts sets A and B were 100 mm and 60 mm long with thread lengths of 2 d + 6 (mm) and 1½ d (mm) respectively. These were produced by cold forging steel bar supplied to BS3111:Part 1:Type 9[6] followed by quenching from an austenising temperature of 850°C and subsequently tempered between 450 - 500°C.

Bolts in Set C were also 100 mm long with a thread length of 2 d + 6 (mm). In contrast, these had been hot forged from steel bar supplied to BS970:Part 1:Grade 150M36[7] (previously En15), quenched from 900°C and tempered at 600 - 620°C.

Details of the chemical compositions for the three sets of bolts are given in Table 4.

Two sets of M20 nuts were used in the test programme. One set was supplied black and had been hot forged from steel bar meeting BS970 : Part 1 : 080M30 (previously EN5) quenched from 870°C and tempered at around 540°C. The second set of nuts was supplied with a bright finish and these were produced by cold forging steel bar meeting BS3111 : Part 1 : Type O.

Chemical compositions for the two sets of nuts are also given in Table 4.

3. ELEVATED TEMPERATURE TEST METHODS

3.1 Component Tests

3.1.1 Tension

Figure 1 shows the loading arrangement in which Nimonic couplings were used to pull nut and bolt assemblies in axial tension. In tests using the long threaded bolts, the length of free thread under tension was 20 mm (d). However, for testing the shorter bolts, this dimension was reduced to 10 mm ($\frac{1}{2}$ d) to ensure that the threads in the nuts were fully utilised. Each set of bolts was evaluated over the temperature range 20 - 800°C in combination with the nuts as summarised below:

Bolt Set	Black Nut	Bright Nut
A	✓	✓
B	✓	✓
C	✓	×

Although no standard specifically covers the testing of structural bolts at elevated temperatures, where appropriate, the methods described in BS3688:Part 1[(8)] were followed.

Each bolt assembly was heated to the desired temperature at a rate of 5 - 10°C/min and stabilised for a period of 15 min to establish a uniform temperature distribution. Since it was impractical to use extensometers, the tests were carried out under displacement control in which a nominal strain rate of between 0.001 - 0.003/min measured in the elastic region, was adopted. Beyond the elastic limit, this rate of straining was maintained until the ultimate capacity was exceeded.

In order to assess whether strength is dependent upon the heating conditions, the programme included several tests in which the bolts were heated at a slower rate of 2 - 2.5°C/min followed by a soaking period at temperature, for a minimum of 60 min.

3.1.2. Double Shear

Tests in double shear were also conducted over the temperature range 20 - 800°C using the general arrangement shown in Fig. 2.

Each joint comprised a 25 mm plate sandwiched between two 12 mm plates and held together by the test bolt and a finger tightened nut. The plates were machined from material supplied to the steel quality BSEN10025:Grade 510B[(9)] and sized so that they exceeded the minimum requirements of BS5950:Part 1[(10)] as well as providing sufficient capacity to rupture the bolts.

In the programme, bolts were tested with both shear planes acting across the shank as well as across the shank and thread. This second arrangement was achieved by placing a spacer between the bolt head and plate so that the position of the thread run-out into the shank was located at mid-thickness of the 25 mm plate. A summary of the test configurations is given below:

Bolt Set	Shear Planes	
A	Shank + Shank	Shank + Thread
C	Shank + Shank	-

The joints were heated as before and held constant at the required temperature for 15 min prior to loading. Testing was conducted under displacement control at a strain rate of 0.001 - 0.003/min measured during the elastic deformation, and was maintained until failure occurred. A new set of plates was used for each test.

3.2 Material Tests

Elevated temperature tensile tests were carried out in accordance with BS3688:Part 1 on round turned specimens machined from the 100 mm long bolts in sets A and C. These were conducted over the temperature range 20 - 800°C at increments of 50°C and for the majority of temperatures, the tests were duplicated. The specimens were strained at a rate of 0.002/min to provide proof stress values up to 5% beyond which, the strain rate was raised to nominally 0.1/min until rupture.

4. POST FIRE EVALUATION

One of the test methods employed to assist in establishing the residual strength of steelwork after fire is to determine its hardness on a finely ground or polished surface.

Following the components tests, each bolt was sectioned through the shank and a hardness profile established by conducting a series of nine Vickers hardness indents (HV30) across the diameter. To extend the data beyond 800°C, additional bolts were heated at temperatures up to 900°C for 30 min (i.e. approximately equivalent to the time spent at temperature prior to and during the component tests). These were slowly cooled back to ambient temperature and evaluated in the same manner.

5. RESULTS AND DISCUSSION

5.1 Tension Tests

Figures 3 - 5 illustrate the influence of temperature on the strength behaviour for each nut and bolt combination acting in tension. A similar pattern of behaviour is observed for all the curves which show a marked loss in strength between 300°C and 700°C. Figure 3 also demonstrates the slower heating rate and the prolonged soaking period had little influence on ultimate capacity.

Test involving bolt sets A and B in combination with the black nuts, failed by ductile necking in the thread at all temperatures, Fig. 6. In contrast, failure of the same bolts using the bright nuts occurred entirely by stripping of the threads, Fig. 7. While the latter resulted in a significant loss in capacity at the low temperatures of up to 20%, above 400°C the effect was far less pronounced and represents a reduction in strength equivalent to a shift in temperature of less than 25°C.

This behaviour suggests a weakness in the thread of the bright nuts yet hardness checks confirmed that not only were they well within specification, but gave similar values to the black heat treated nuts. In addition, tests using the bolts in Set C with only the black nuts, Fig. 5, resulted in both modes of failure.

Metallographic sections were prepared from selected test pieces to examine the failures in more detail.

Figures 8 and 9 are typical sections through the threads in the black nuts and bolts which failed by ductile necking. The contact areas between the two components and the resulting plastic deformation in the threads, are clearly evident.

Figures 10 and 11 are similar sections prepared from the bright finished nuts and bolts which failed by the threads being stripped. These show the extent of plastic deformation was so severe that the threads in both components had in effect, sheared.

The observations described indicate neither the nuts nor the bolts were solely responsible for causing premature failure in the threads but their behaviour was controlled by the overall interaction between the two components. Clearly a close fitting nut and bolt provides a greater surface contact area between the threads thereby spreading the load and effectively reducing the stresses.

In BS5950:Part 1, the capacity of bolts in tension (P_t) is given by the relationship:

	P_t	$= p_t A_t$
where	A_t	= tensile stress area (M20 bolts = 245 mm^2)
	p_t	$= 0.58\, U_f$ but $\leq 0.83\, Y_f$
and	U_f	= specified ultimate tensile strength
	Y_f	= specified yield or 0.2% proof stress

For grade 8.8 bolts in which $U_f = 785$ N/mm^2 and $Y_f = 628$ N/mm^2, the ultimate tensile strength controls and therefore, the tension capacity of M20 bolts at ambient temperature = 111.6 kN. At the fire limit state, P_t can be multiplied by 80% of the strength reduction factor corresponding to 0.5% strain for structural steel (Table 1) to derive the design curve. The resulting relationship is illustrated in Fig. 12 as a function of temperature and is compared with the best fit lines for the measured ultimate capacities from Figs. 3 - 5. To provide a realistic comparison with the likely response of bolts supplied with minimum specified properties, the test data have also been normalised with respect to:

ultimate tensile strength	=	785 N/mm^2
net cross-section area	=	245 mm^2

With the exception of tests carried out at temperatures in the region of 700°C, the capacity of the black nuts and bolts indicate a considerable redundancy at the fire limit state and there appears to be a case for raising the design curve at low to intermediate temperatures. The smallest margin of safety of ~35% occurred at 680°C and although this is not unsatisfactory, there is little justification for raising the design curve at the higher temperatures evaluated.

In tests involving the bright finished nuts, there is also considerable redundancy for the majority of the temperature range despite the threads between the two components stripping. However, other combinations of nuts and bolts may fail prematurely at lower loads and while these appear unlikely to fall below the design curve, some uncertainty concerning their integrity will remain, particularly if the design curve is raised to a higher level.

Since it would be unrealistic to evaluate the entire market of grade 8.8 nuts and bolts there is a practical solution to improving the integrity of the threads. This may be achieved by specifying the nut and bolt dimensional properties to the tighter tolerance classes of BS3692 (i.e. 6H/6g - BS3643:Part 2[(11)]). Alternatively, further surety is obtained by using nuts supplied to the higher strength grade-BS4395:Part 1[(12)]. These also provide a greater thread length to withstand the high torquing loads normally applied in service.

5.2 Shear Tests

The influence of temperature on the behaviour of grade 8.8 bolts in double shear is illustrated in Figs. 13 and 14. A similar pattern of behaviour to the tension tests is observed in which a marked loss in capacity is experienced over the temperature range 300 - 700°C.

During the tests considerable prying action occurred, Fig. 15, which often resulted in part of the bolt flying out at high velocity. Precautions therefore had to be taken to protect the furnace elements.

For the test configurations in which both shear planes acted through the shank, either one or both planes fractured, Fig. 16. However, in tests involving shear across the thread, despite this shear path initially having a lower capacity, failure also often occurred in the shank, Fig. 17. This was due to the tensile stresses generated by the prying action causing the bolt thread to extend thereby forcing the connecting plys out of alignment. The resulting effect of the reduced section across the thread was only a marginal reduction in capacity at temperatures above 350°C and is a reflection of the increased ductility of the bolt material.

In BS5950:Part 1, the capacity of bolts in shear (P_s) is given by the relationship:

$$P_s = p_s A_s$$

where A_s = shear area (M20 bolts = 245 mm^2 and 288 mm^2 for thread and shank respectively)

p_s = $0.48\, U_f$ but $\leq 0.69\, Y_f$

Substituting values of U_f = 785 N/mm^2 and Y_f = 628 N/mm^2 for grade 8.8 bolts, the ultimate tensile strength controls and therefore the capacity of M20 bolts in double shear = 200.8 kN or 217.0 kN for the shear conditions: shank + thread and shank + shank respectively.

At the fire limit state, the capacity of bolts is again derived from 80% of the strength reduction factor corresponding to 0.5% strain for structural steel. The resulting curves are illustrated in Fig. 18 and are compared with the test results normalised with respect to bolts supplied with minimum dimensional and strength properties. At low to intermediate temperatures, the experimental data given illustrate the conservative nature of the present guidelines. With premature failure in the threads not being important, there is a stronger case for designing to a greater capacity over the majority of the temperature range. In the case of the higher temperatures i.e. at 685°C in particular, the present design curves offer a minimum safety margin of 25%.

5.3 Material Tests

The results of the elevated temperature test on the machined test pieces are presented in Figs. 19 and 20 for bolt Sets A and C respectively. In each case, curves corresponding to proof stress values of 0.2%, 1%, 2% and 5% are given. These illustrate a low rate of net hardening at temperatures above 400°C with the result there is little difference between the 0.2% proof stress and those values corresponding to higher strains. In fact by using a strain rate of 0.002/min above 400°C the ultimate tensile strength was achieved prior to 5% being attained.

Both sets of bolts were supplied with properties well above the specified minima and therefore the curves for 0.2% proof stress have been normalised with respect to the minimum ambient temperature requirement, Fig. 21. Despite the different processing and heat treatment conditions used in manufacture, the two sets of bolts show similar behaviour at temperatures above 400°C where their performance under fire conditions can be more critical.

For comparison, the maximum allowable stress is tension under the old BS449:Part 2[13] design rules is indicated as well as that which could be imposed using BS5950:Part 1 with a load factor of 1.4. At maximum working loads the critical temperature for the onset of plastic deformation is in the region of 500°C.

5.4 Post Fire Residual Properties

Figure 22 illustrate the residual hardness as a function of temperature measured using the components tests from bolt Set A. The results emphasise the sensitivity of the mechanical properties in quench and tempered steels to overheating. In contrast, hot rolled structural steels are relatively unaffected by fire until 600°C is exceeded(3) and even then, the changes are far less dramatic.

Heating bolts to below their tempering temperature will have little effect on their properties over a short period of time. Between the tempering temperature (i.e. >500°C for bolt Set A) and transformation there will be a loss in hardness and consequently strength which is associated with the further formation and continued growth of carbides (spheroidisation/Oswald ripening). At the higher temperatures viz ~800/900°C the benefits of the hardening process have been lost and the properties are more akin to a hot rolled structural steel. Figures 23(a), (b) and (c) show some of the changes in microstructure.

Relationships between time and temperature in the heat treatment of steels are well established based largely on work originally reported by Hollomon and Jaffe(14). These are used by manufacturers in the choice of composition and processing conditions to obtain the desired properties in steel components. Since the residual hardness and strength of heat treated bolts are sensitive to temperature, use can be made of the metallurgical changes to establish the temperatures attained at connections during the fire process. The information can also be used in assessing the behaviour of steel structures during post fire investigation and reinstatement.

6. POST FIRE EVALUATION OF BOLTS

Simply comparing the hardness profile of one bolt to another to determine whether a fire has had an affect upon the properties would not provide an answer; it assumes the bolts were manufactured under identical conditions. Even bolts supplied from the same batch as used in this investigation, show a large scatter in results, Fig. 22, and without prior knowledge of their tempering temperature, they could be heated up to nearly 600°C before a change in hardness would appear significant.

With the difficulties highlighted above, a technique has been established whereby the highest temperature achieved by a bolt either during the tempering process or in a fire, can be determined. The procedure makes use of the fact that changes in hardness are far more sensitive to temperature rather than time.

Three bolts from Set A were sectioned into a series of slices and heated at various temperatures up to 750°C for 30 min. Once cooled back to ambient temperature a hardness profile was established as before.

Figure 24 illustrates the change in average hardness across each slice as a function of temperature. By careful selection, the actual tempering temperature can be identified from the intersection of the two lines, A - B, when a further rise in temperature would cause a loss in hardness. Had these bolts been in a fire and attained a higher temperature than that used in tempering during manufacture, there would be no further change in hardness until it was exceeded by the subsequent heat treatment.

Having determined the maximum temperature for which there is no change in hardness, it would then be a case of identifying from the composition, the normal range of tempering temperatures. This would establish either the temperature attained by the bolt during the fire process or if lower than the tempering temperature, an upper limit.

Confirmation that softening of heat treated bolts is relatively insensitive to time for the periods of heating normally experienced in a fire, a further series of slices from two bolts were heated at various times both above and below their tempering temperature viz 550°C and 430°C. The results given in Table 5 show only small changes do occur with time.

7. CONCLUSIONS

The behaviour of high strength Grade 8.8 bolts at elevated temperatures has been investigated to provide data for designing at the fire limit state.

Tests in double shear and tension using M20 size nuts and bolts have highlighted a marked loss in ultimate capacity between 300°C and 700°C.

When the results are normalised with respect to the specified minimum strength and dimensional tolerances, they show that the present design curves based upon BS5950:Part 8 are conservative, particularly at the low to intermediate temperatures. There is a case for amending these to a higher level should the Standard be revised at a later date. In addition, by analysing the data in this manner, it is shown for temperatures above 300°C the different processing conditions used in manufacturing the bolts had little influence on their ultimate capacity.

Tests in tension have highlighted the problems of premature failure by thread stripping. This was found to be controlled by the interaction of the threads between the nut and bolt rather than the fault of an individual component. The effect on capacity is difficult to quantify and therefore where the full capacity of the bolts in tension is required it is recommended the components are supplied to at least the dimensional tolerances given in BS3692 and preferably, with the nuts supplied to the higher strength Grade BS4395:Part 1.

Elevated temperature proof stress data is provided from tensile tests using machined specimens. For the maximum design stresses used in construction and with bolts supplied with minimum properties, the onset of plastic deformation will be expected to occur at temperatures around 500°C. In this region the different manufacturing processing conditions again have only small influence on the results.

The residual hardness of bolts subjected to heating have been examined in detail for post fire investigation purposes. Where the temperature in fire exceeds the tempering temperature used in manufacture, further softening of the bolt occurs. A technique is introduced whereby it is possible to establish the actual temperature a bolt may have achieved in a fire or if this is lower than the tempering temperature, then an upper limit based upon known manufacturing processes.

All the tests have been conducted using M20 size components. While other sizes are used it is recommended for the time being the strength data be used for nut and bolt sizes up to M30. For larger bolt diameters it would be prudent for some limited further testing.

B.R. Kirby
Senior Investigator

D.J. Price
Research Manager
General Steel Products

ACKNOWLEDGEMENTS

The author acknowledges Mr I. Tomlinson who conducted the majority of the test work and Mr M. Tiddy at Cooper and Turner for helpful comments as well as supplying some of the components.

REFERENCES

1. BS3692, 'ISO Metric Precision Hexagon Bolts, Screws and Nuts', British Standards Institution, 1967.

2. BS5950, 'Structural Use of Steelwork in Building, Part 8: Code of Practice for Fire Resistant Design', British Standards Institution, 1990.

3. B.R. Kirby, D.G. Lapwood and G. Thomson, 'The Reinstatement of Fire Damaged Steel and Iron Framed Structures', British Steel Technical, Swinden Laboratories, 1986.

4. R.A. Brash, 'The Residual Shear Strength of Grade 8.8, M20 Bolts Following Fire Simulation Treatments', British Steel Technical Report No. SL/RS/R/S1199/13/89/B, 1989.

5. BS4190, 'ISO Metric Black Hexagon Bolts, Screws and Nuts', British Standards Institution, 1967.

6. BS3111, 'Steel Wire for Cold Forged Fasteners and Similar Components, Part 1: Carbon and Low Alloy Steel Wire', British Standards Institution, 1987.

7. BS970, 'Wrought Steels for Mechanical and Allied Engineering Purposes, Part 1: Hot Rolled and Normalised Steels', British Standards Institution, 1983.

8. BS3688, 'Methods for Mechanical Testing of Metals at Elevated Temperatures, Part 1: Tensile Testing', British Standards Institution, 1963.

9. BSEN10025, 'Hot Rolled Products of Non-alloy Structural Steels and their Technical Delivery Conditions', British Standards Institution, 1990.

10. BS5950: 'Structural Use of Steelwork in Building, Part 1: Code of Practice for Design in Simple and Continuous Construction: Hot Rolled Sections', British Standards Institution, 1990.

11. BS3643, 'ISO Metric Screw Threads, Part 2: Specification for Selected Limits of Size', British Standards Institute, 1981.

12. BS4395, 'High Strength Friction Grip Bolts, Part 1: General Grade', British Standards Institution, 1969.

13. BS449, 'The Use of Structural Steel in Building, Part 2: Metric Units', British Standards Institution, 1969.

14. J.H. Hollomon and L.D. Jaffe, 'Time-Temperature Relations in Tempering Steel', Metals Technology, 1945, (12) Sept., AIME, Technical Publication No. 1831.

C.D.

TABLE 1
STRENGTH REDUCTION FACTORS FOR GRADE 8.8 BOLTS AT THE FIRE LIMIT STATE, BS5950:PART 8[2]

Temperature °C	Strength Reduction Factor
20	0.800
100	0.776
150	0.767
200	0.757
250	0.707
300	0.683
350	0.661
400	0.638
450	0.577
500	0.498
550	0.394
600	0.302
650	0.215
700	0.149
750	0.102
800	0.057
850	0.036
900	0.024
950	0.019

TABLE 2
MECHANICAL PROPERTIES OF NUTS SUPPLIED TO BS3692:GRADE 8.8(1)

Mechanical Property		Requirement
Proof Load Stress		785 N/mm^2
Brinell Hardness HB	max.	302
Rockwell Hardness HRC	max.	30
Vickers Hardness HV30	max.	310

TABLE 3
MECHANICAL PROPERTIES OF BOLTS SUPPLIED TO BS3692:GRADE 8.8(1)

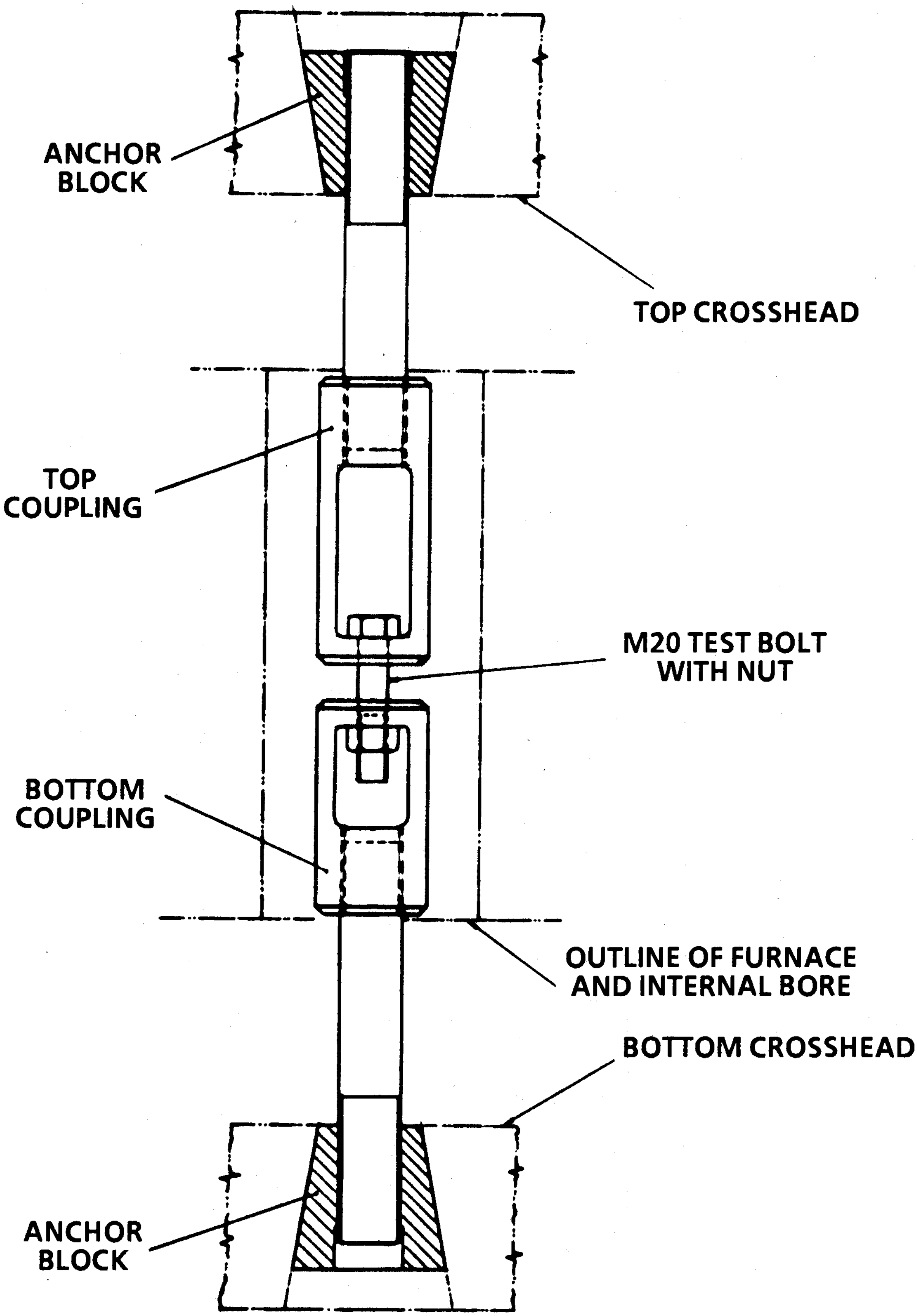
Mechanical Property		Requirement
Tensile Strength R_m	min. max.	785 N/mm^2 981 N/mm^2
0.2% Proof Stress $R_{0.2}$	min.	628 N/mm^2
Stress Under Proof Load S_p		571 N/mm^2
Elongation after Fracture	min.	12%
Brinell Hardness HB	min. max.	225 300
Rockwell Hardness HRC	min. max.	18 31
Vickers Hardness HV30	min. max.	225 300
Charpy Impact Strength	min.	30 J

TABLE 4
CHEMICAL COMPOSITIONS OF THE NUTS AND BOLTS USED IN THE INVESTIGATION

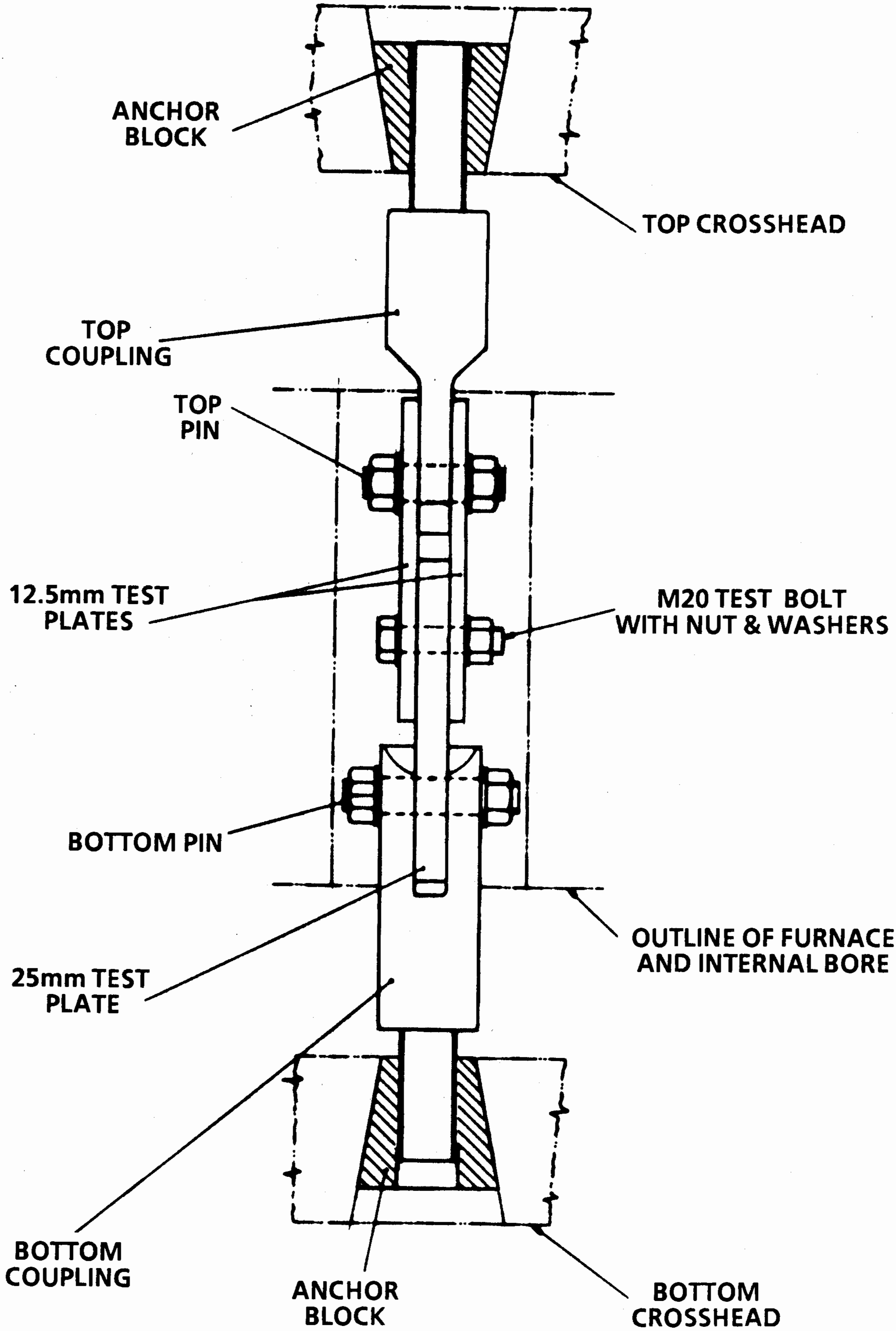
Product	Chemical Analysis in Wt. %														
	C	Si	Mn	P	S	Cr	Mo	Ni	Al	B	Cu	N	Nb	Ti	V
Bolts - Set A	0.19	0.21	1.16	0.020	0.017	0.19	0.027	0.14	0.029	0.0051	0.22	0.0080	<0.005	0.036	0.006
Bolts - Set B	0.21	0.25	1.02	0.009	0.009	0.23	0.021	0.10	0.029	0.0024	0.14	0.012	<0.005	0.042	<0.005
Bolts - Set C	0.41	0.16	1.61	0.021	0.038	0.13	0.13	0.12	0.018	<0.0005	0.23	0.013	<0.005	<0.005	<0.005
Nuts - Black	0.25	0.21	0.77	0.010	0.016	0.06	0.018	0.08	0.017	<0.0005	0.16	0.012	<0.005	<0.005	<0.005
Nuts - Bright	0.18	0.02	0.45	0.024	0.013	0.03	0.005	0.04	0.037	<0.0005	0.04	0.0064	<0.005	<0.005	<0.005

TABLE 5
THE INFLUENCE OF TIME ON THE RESIDUAL HARDNESS OF GRADE 8.8 BOLTS (BOLT SET A)

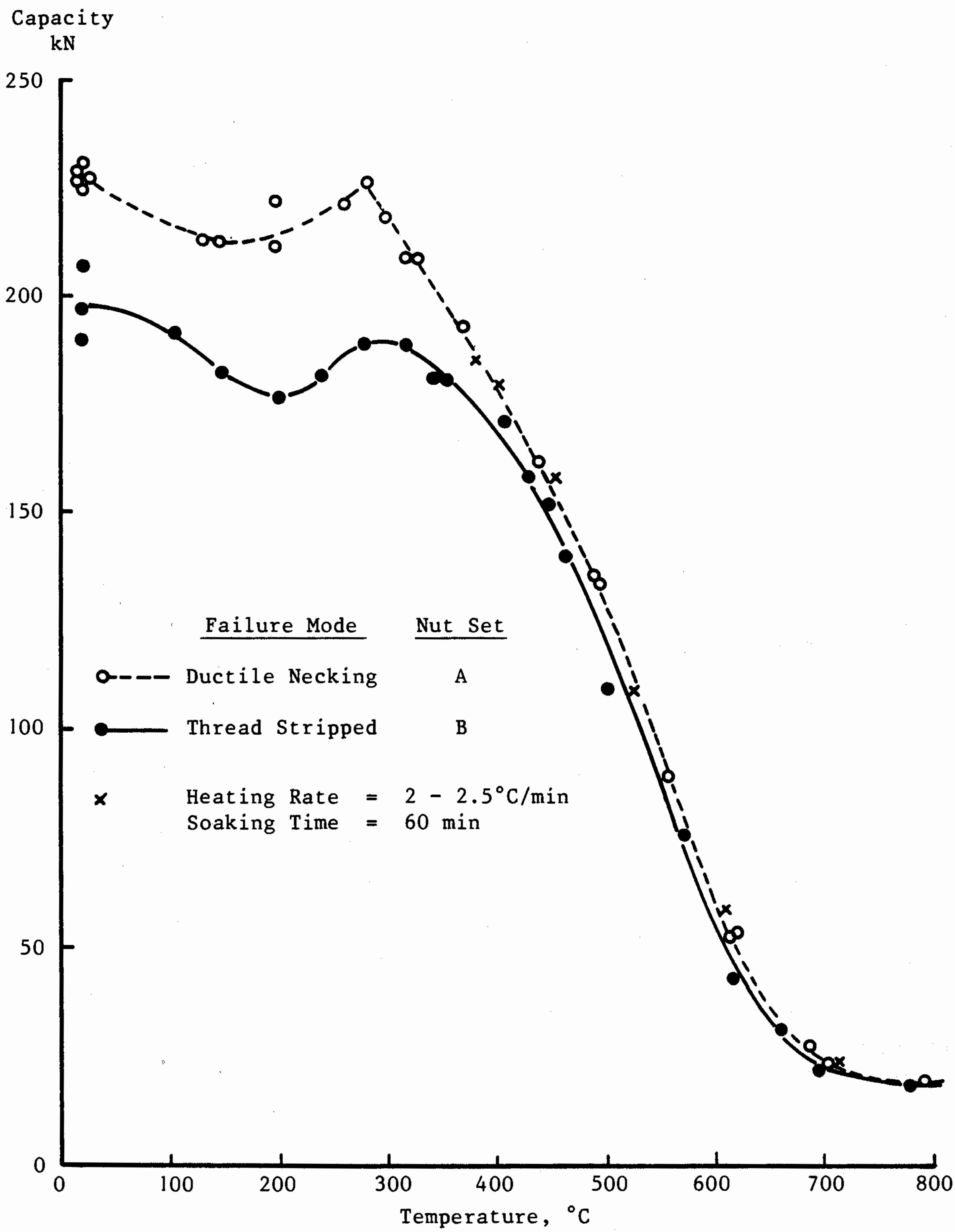
Reheating Temperature	Average Hardness (HV30) for Various Periods of Heating			
	As-Received	30 min	120 min	360 min
430°C	311	313	313	309
550°C	303	270	268	265



TEST ARRANGEMENT FOR EVALUATING BOLTS IN TENSION FIG. 1

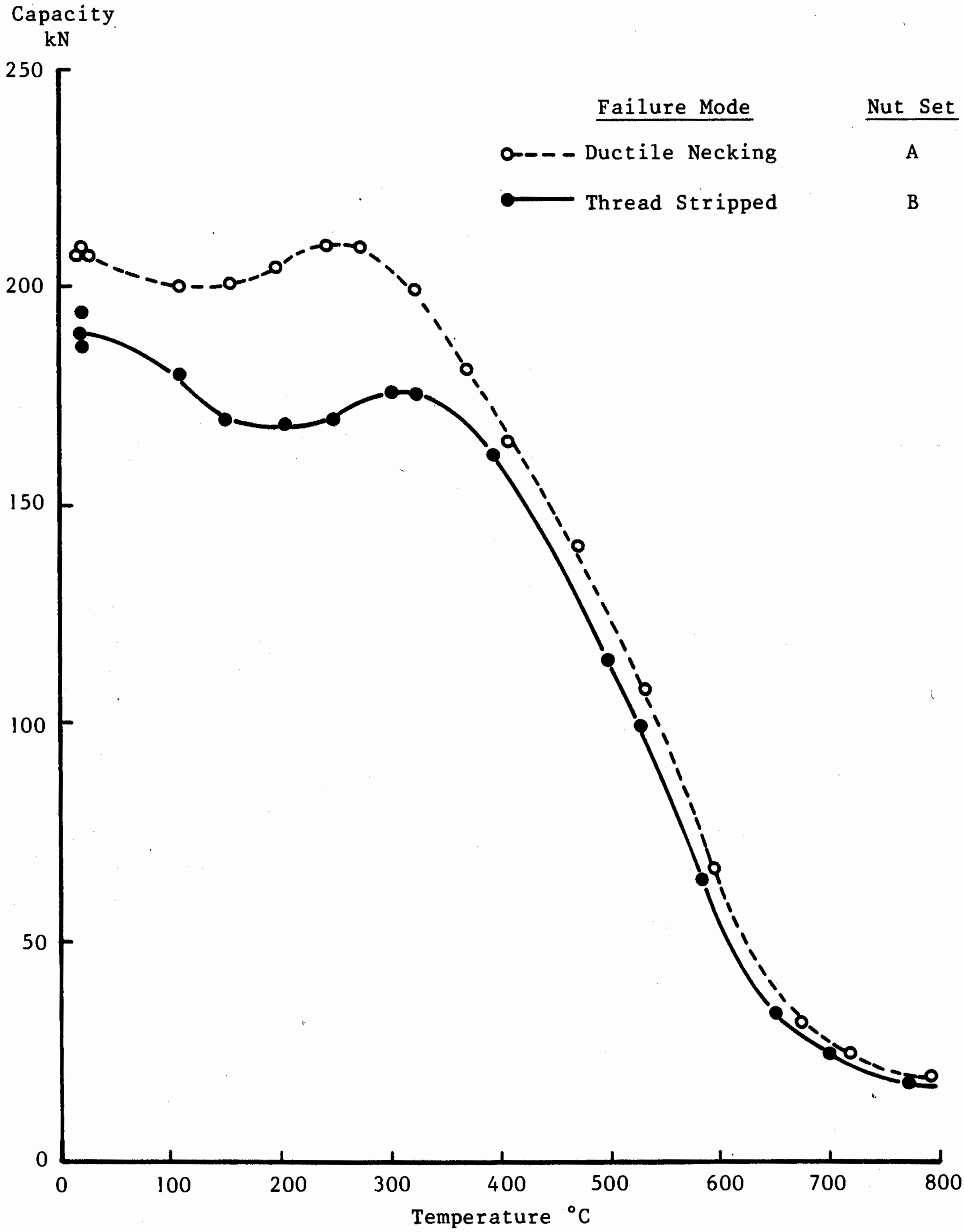


GENERAL TEST ARRANGEMENT FOR EVALUATING BOLTS IN DOUBLE SHEAR FIG. 2



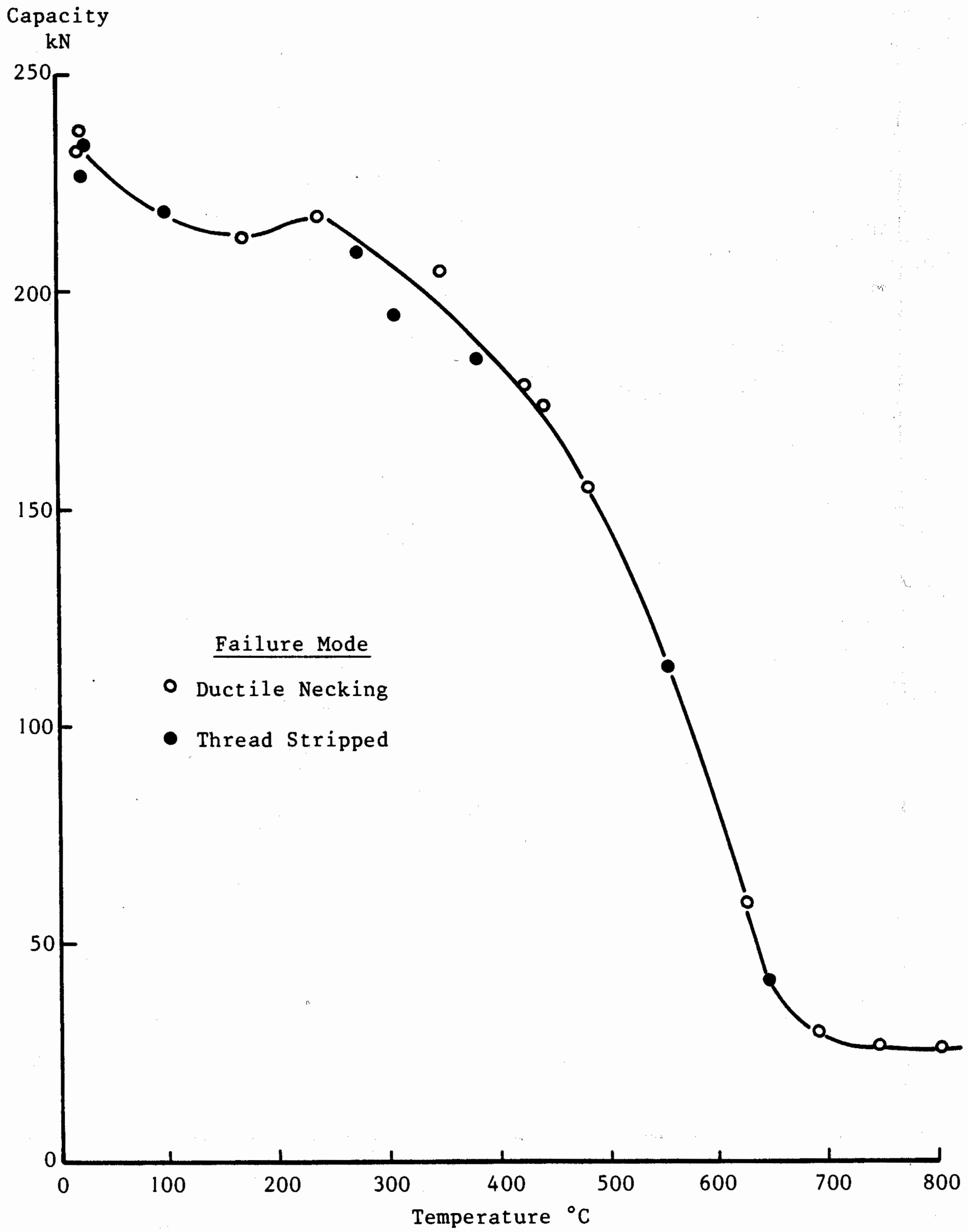
CAPACITY OF HIGH STRENGTH GRADE 8.8 BOLTS IN TENSION AT ELEVATED TEMPERATURES (BOLT SET A)

FIG. 3 (R3/8800)



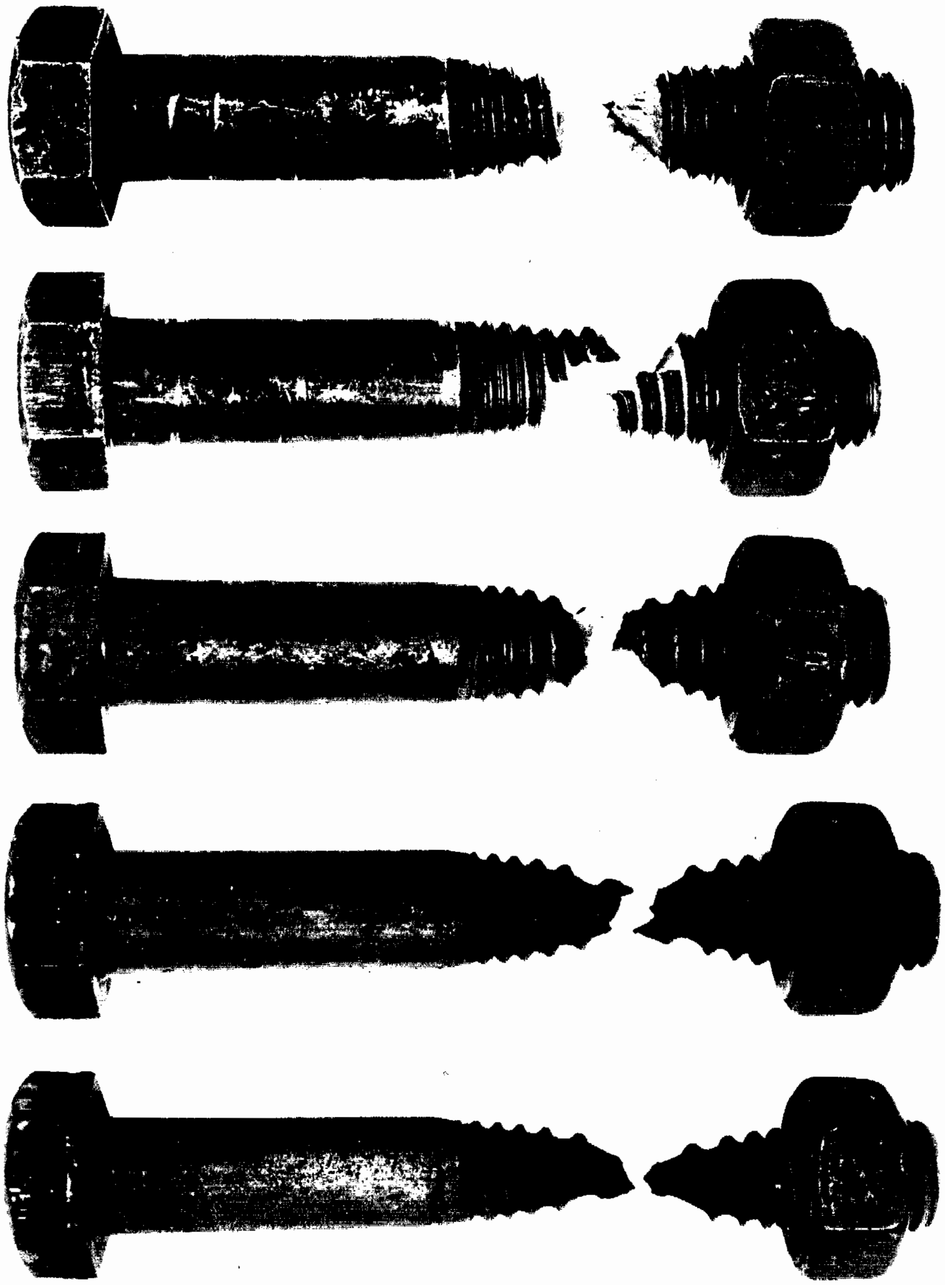
CAPACITY OF HIGH STRENGTH GRADE 8.8 BOLTS IN TENSION AT ELEVATED TEMPERATURES (BOLT SET B)

FIG. 4 (R3/8801)



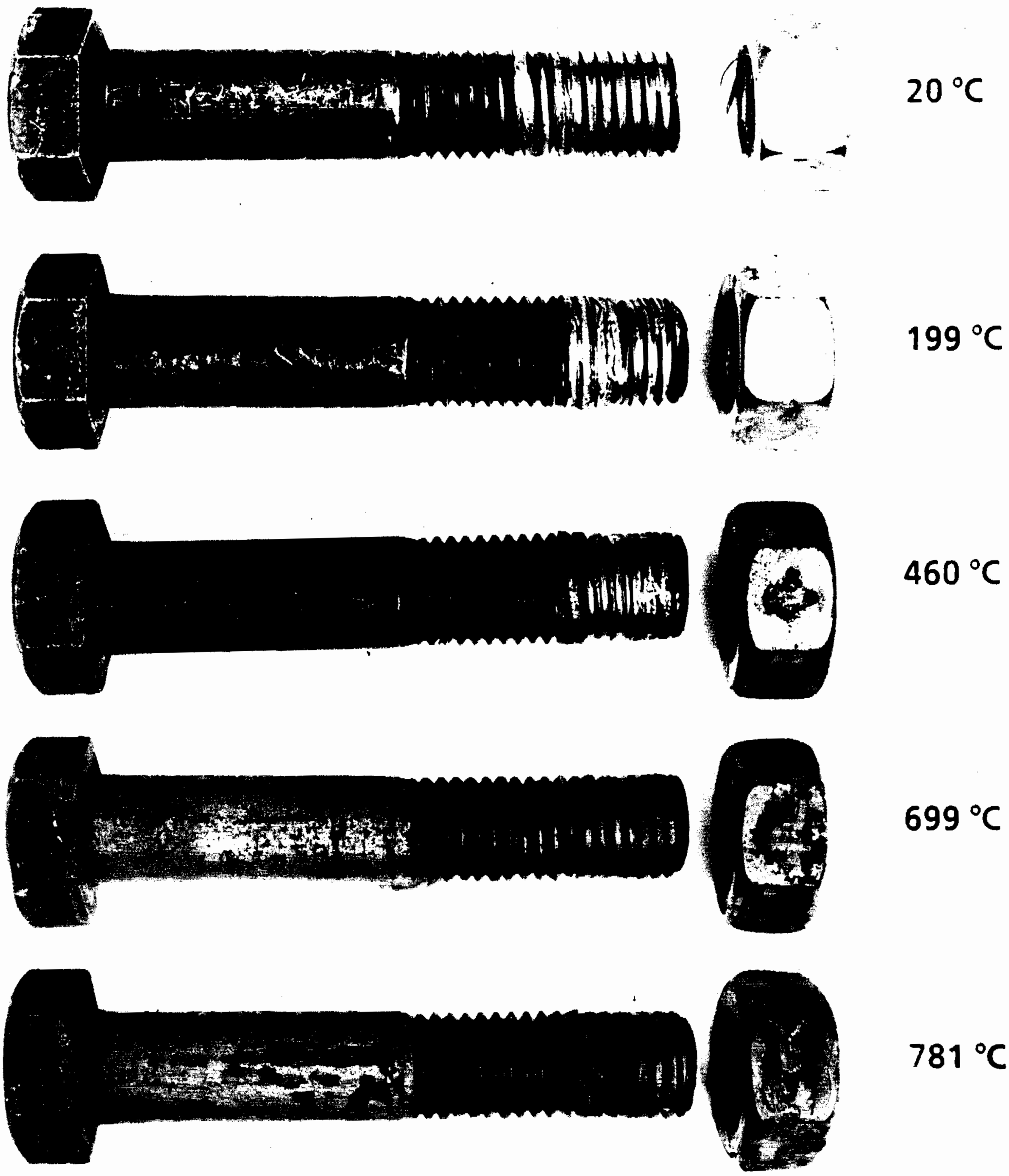
CAPACITY OF HIGH STRENGTH GRADE 8.8 BOLTS IN TENSION AT ELEVATED TEMPERATURES (BOLT SET C, NUT SET A)

FIG. 5 (R3/8802)



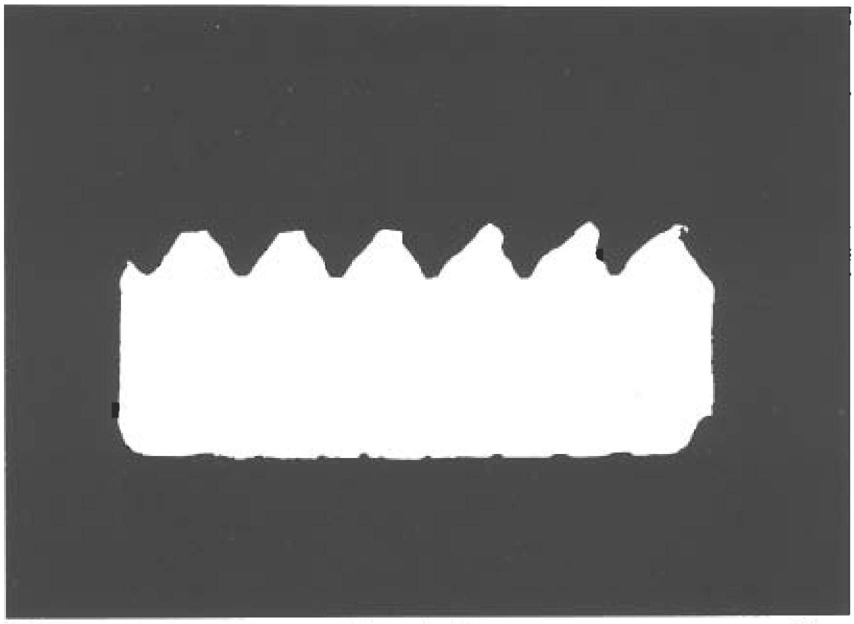
TENSION TESTS IN WHICH FAILURE OCCURRED BY DUCTILE NECKING IN THE BOLT THREAD

FIG. 6

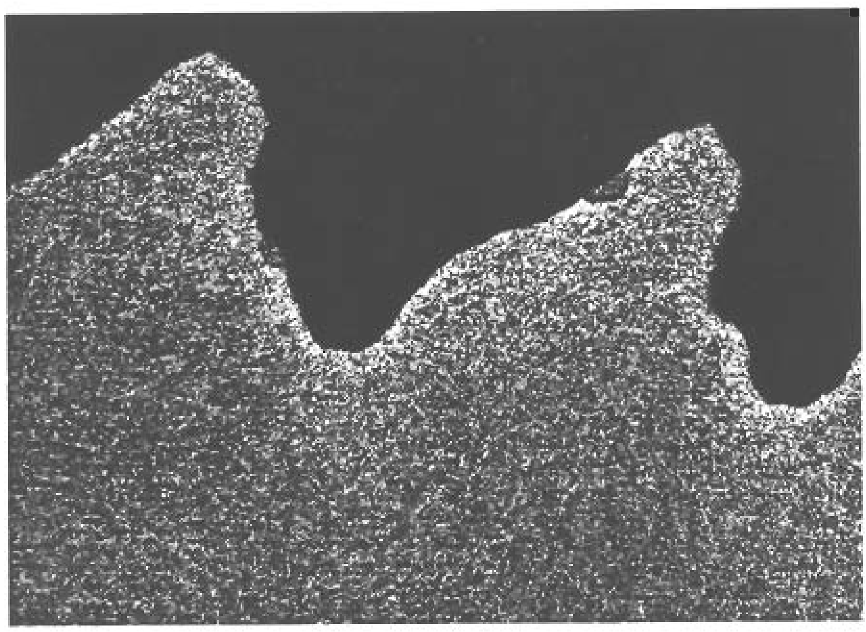


TENSION TESTS IN WHICH FAILURE OCCURRED BY THE THREADS STRIPPING IN BOTH THE NUT AND BOLT

FIG. 7

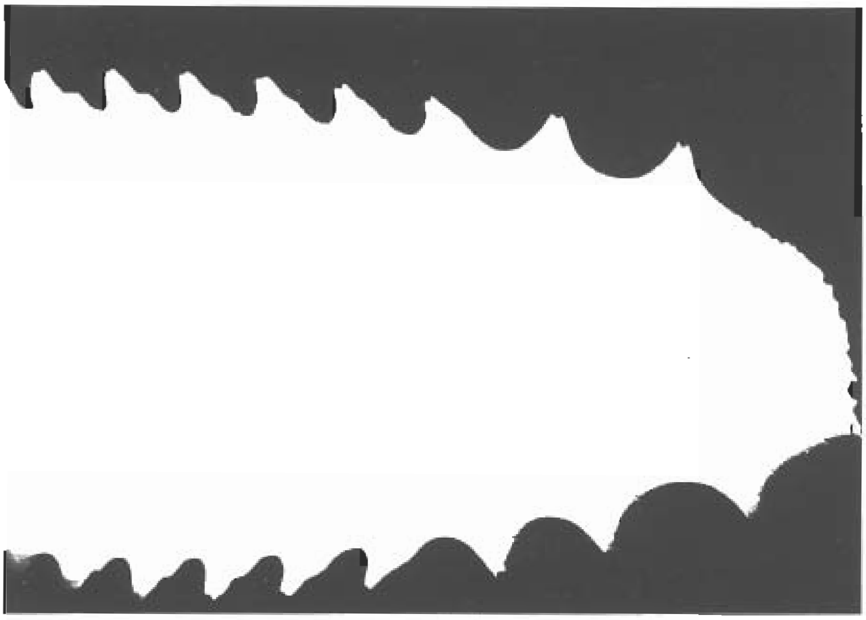


x 5 Unetched (a)

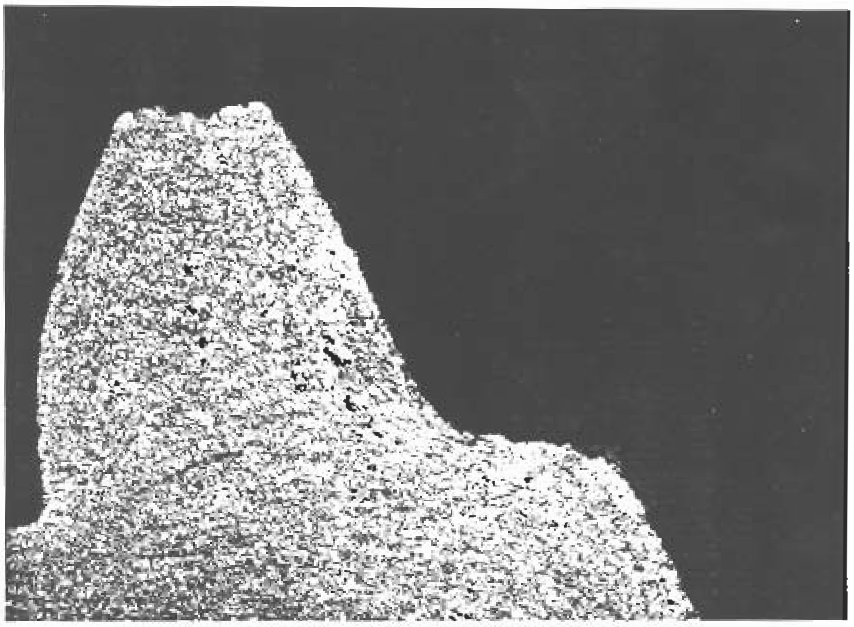


x 25 Etched (b)

SECTION THROUGH A NUT IN WHICH THE BOLT COUNTERPART FAILED BY DUCTILE NECKING IN THE THREAD — FIG. 8

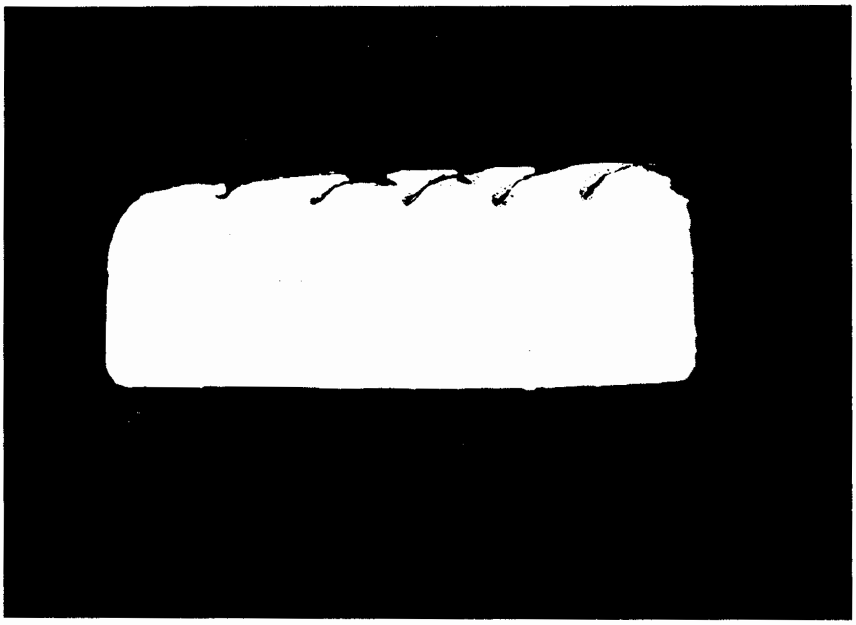


x 3.5 Unetched (a)

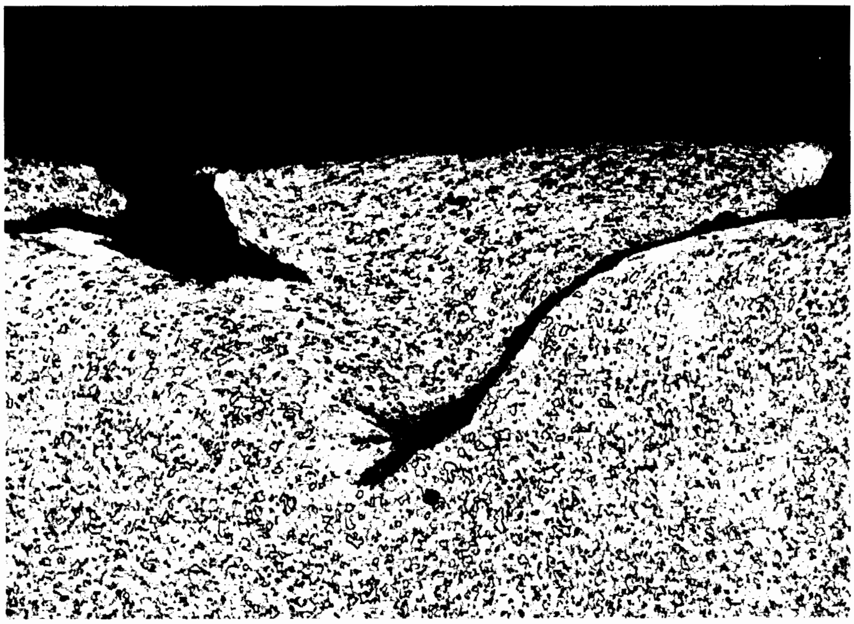


x 50 Etched (b)

LONGITUDINAL SECTION THROUGH A BOLT WHICH FAILED BY DUCTILE NECKING IN THE THREAD FIG. 9

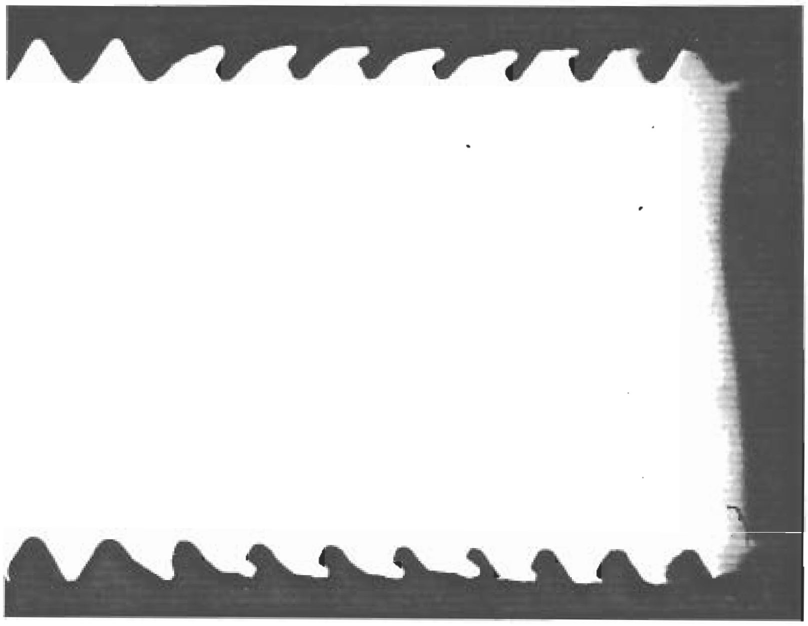


x 5 Unetched (a)

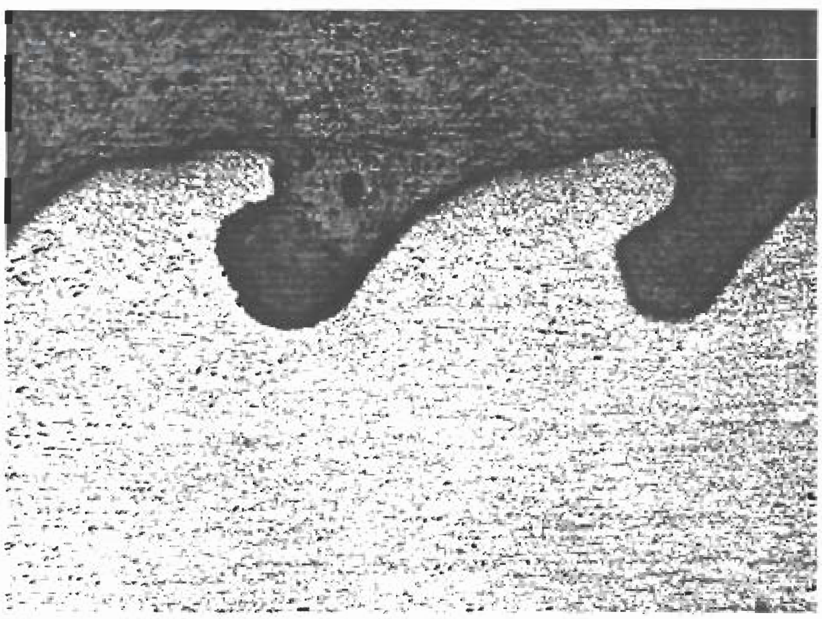


x 50 Etched (b)

SECTION THROUGH A NUT WHICH FAILED BY THE THREADS STRIPPING **FIG. 10**



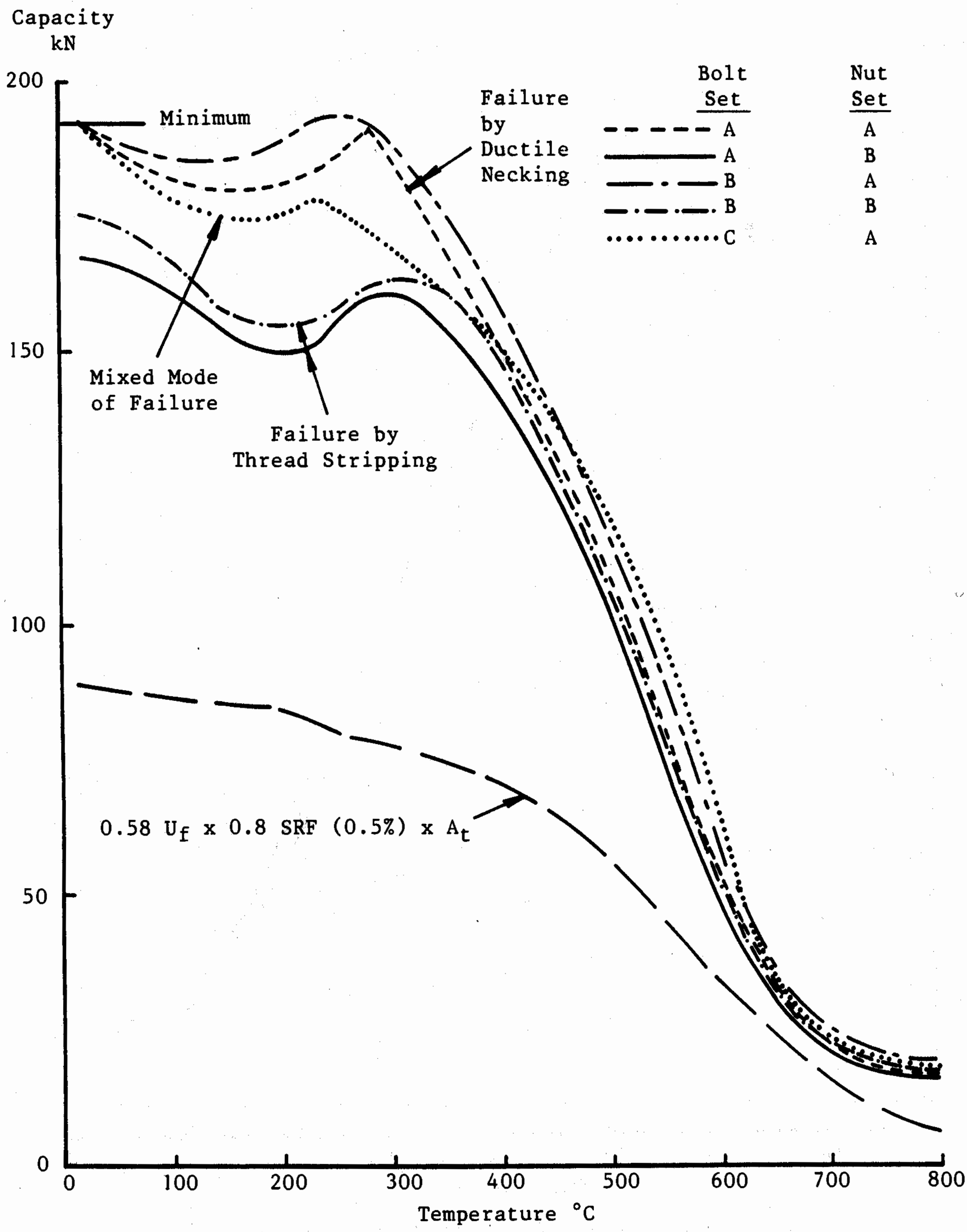
x 3.5 Unetched (a)



x 25 Etched (b)

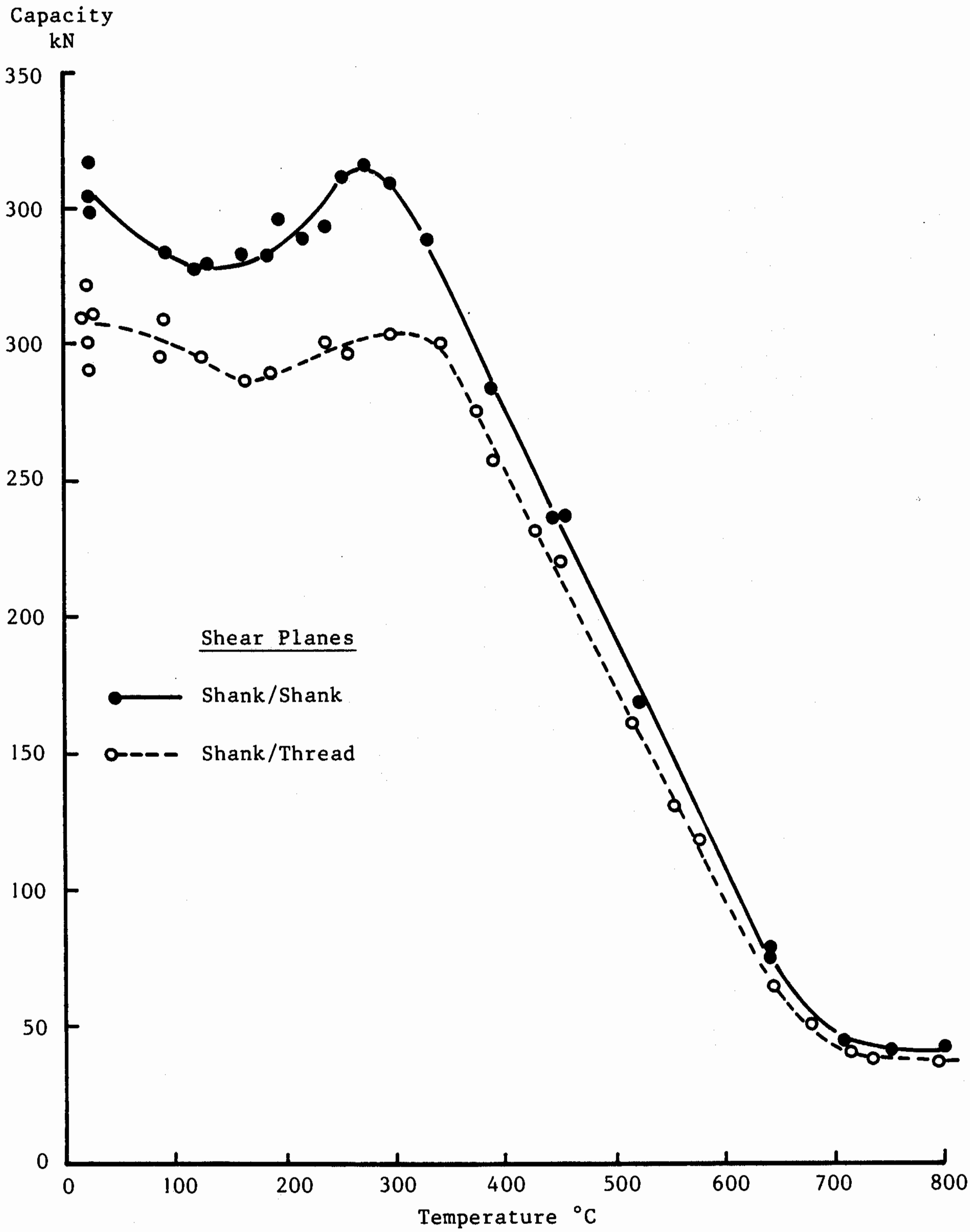
LONGITUDINAL SECTION THROUGH A BOLT WHICH FAILED BY THE THREADS STRIPPING

FIG. 11



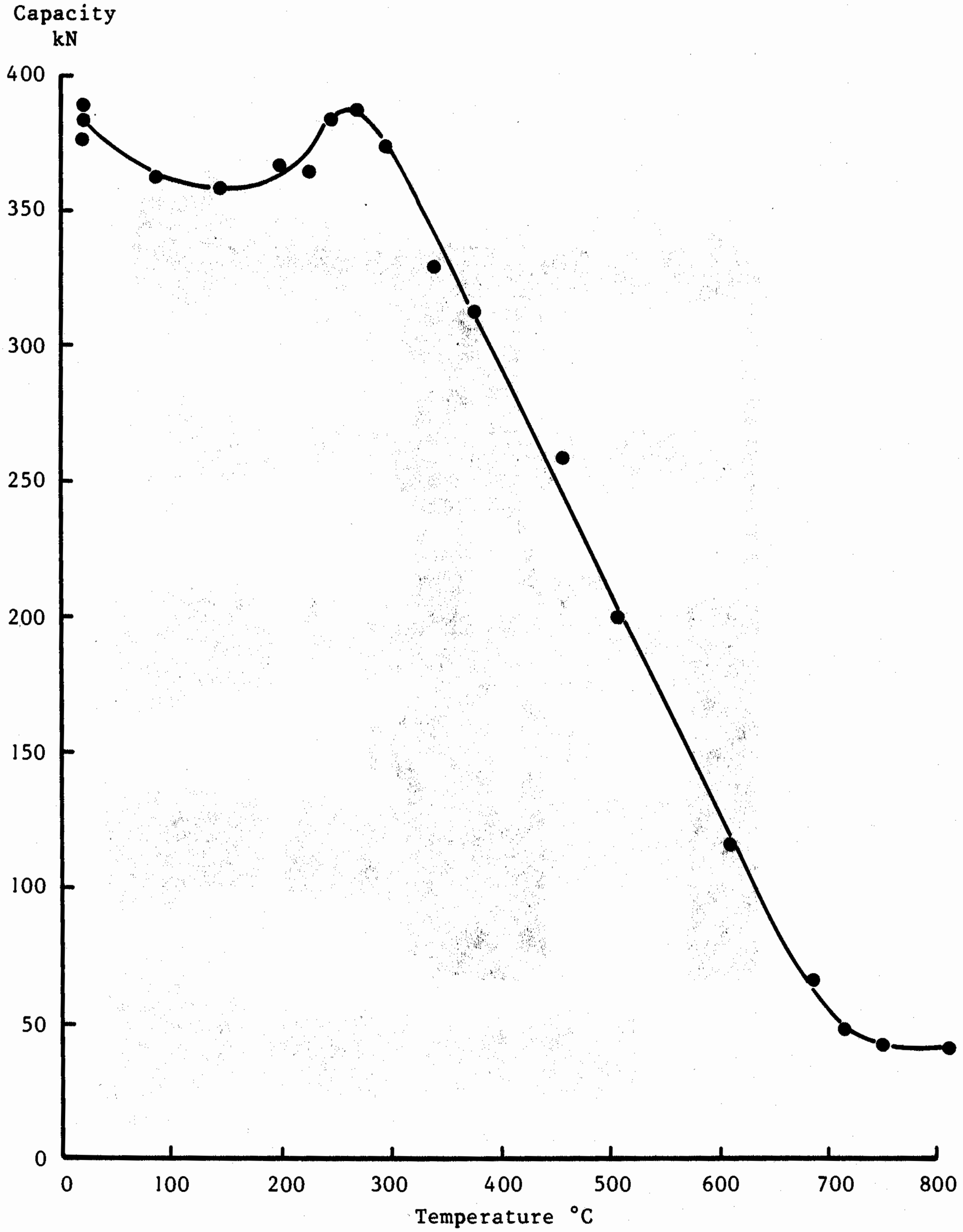
COMPARISON BETWEEN THE FIRE LIMIT STATE DESIGN CURVE AND THE CAPACITY OF GRADE 8.8 BOLTS IN TENSION NORMALISED WITH RESPECT TO MINIMUM STRENGTH AND NET CROSS SECTION AREA

FIG. 12 (R3/8803)



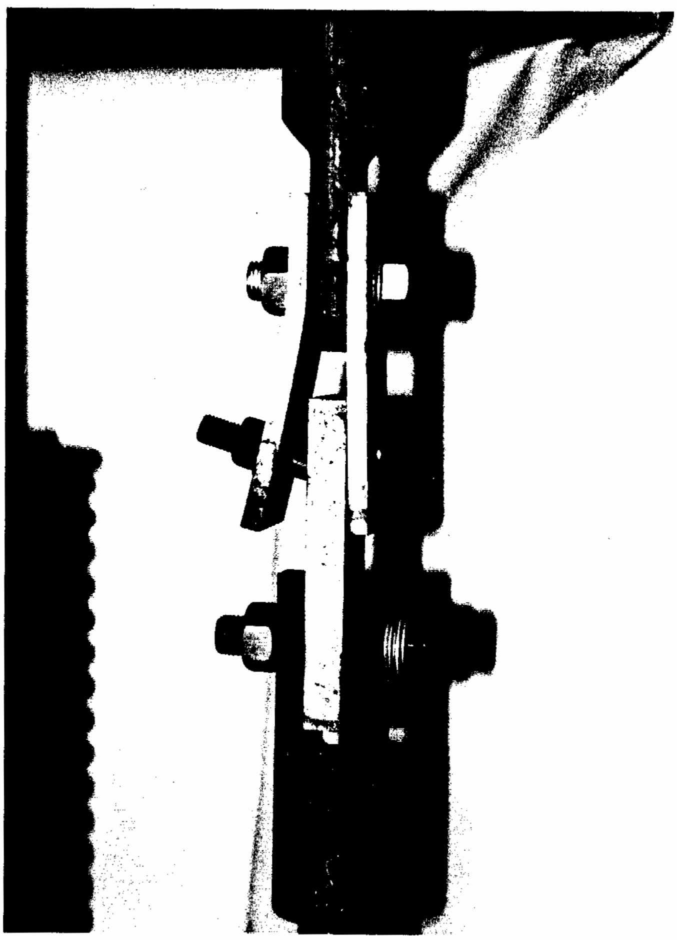
CAPACITY OF HIGH STRENGTH GRADE 8.8 BOLTS IN DOUBLE SHEAR AT ELEVATED TEMPERATURES (BOLT SET A)

FIG. 13 (R3/8804)

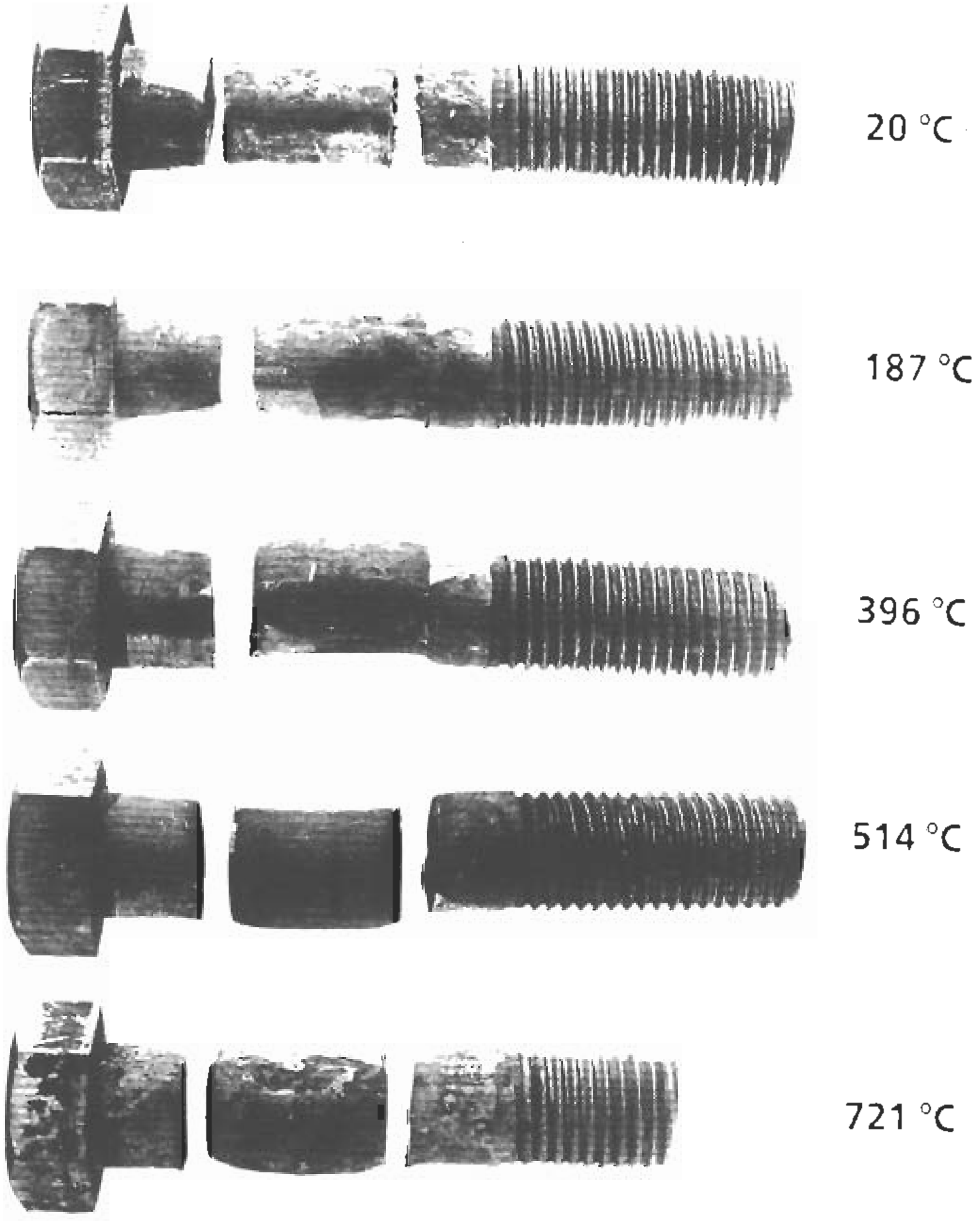


CAPACITY OF HIGH STRENGTH GRADE 8.8 BOLTS IN DOUBLE SHEAR AT ELEVATED TEMPERATURES (BOLT SET C)

FIG. 14 (R3/8805)

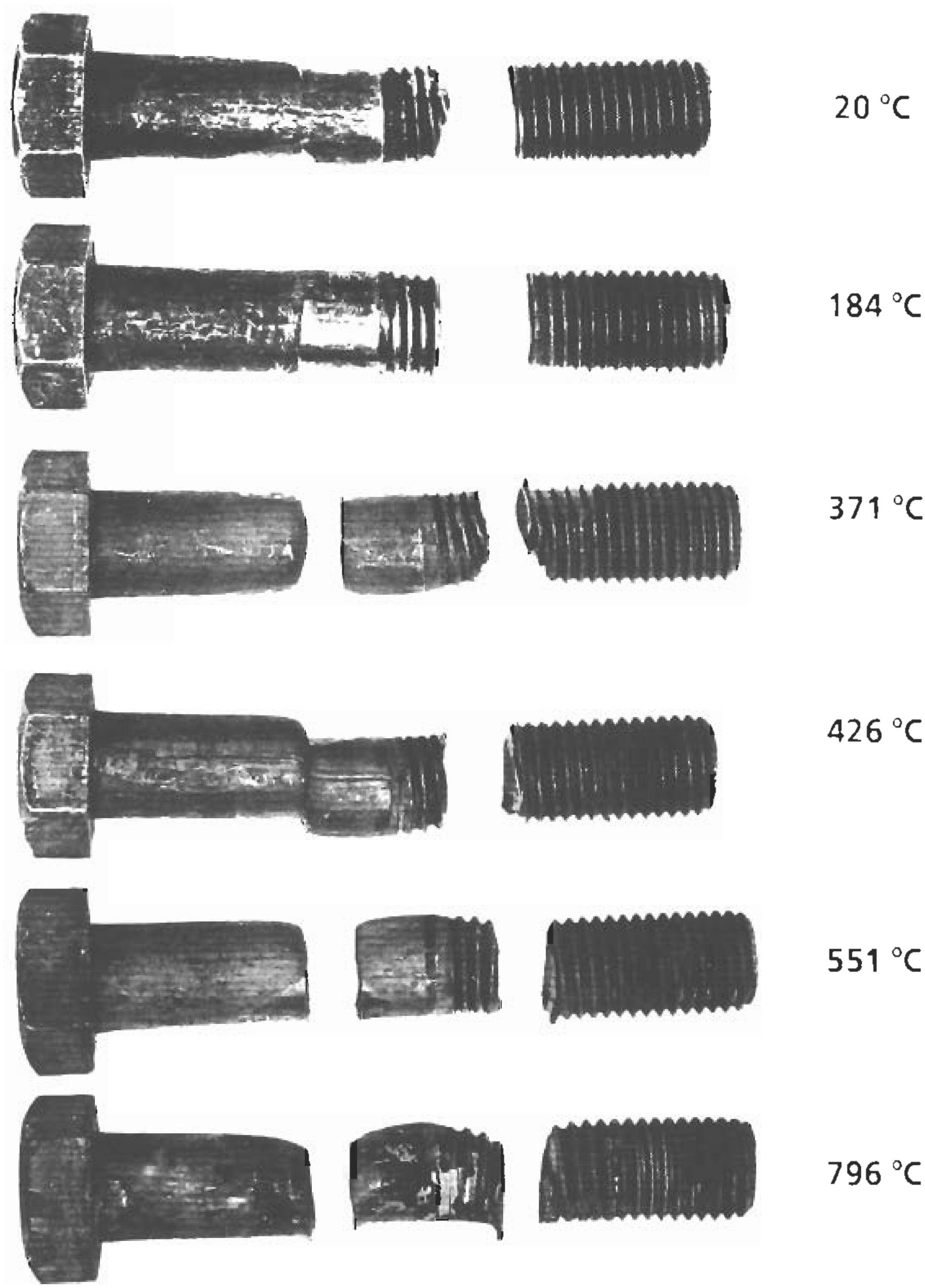


TYPICAL FAILURE OF A BOLTED ASSEMBLY IN DOUBLE SHEAR **FIG. 15**



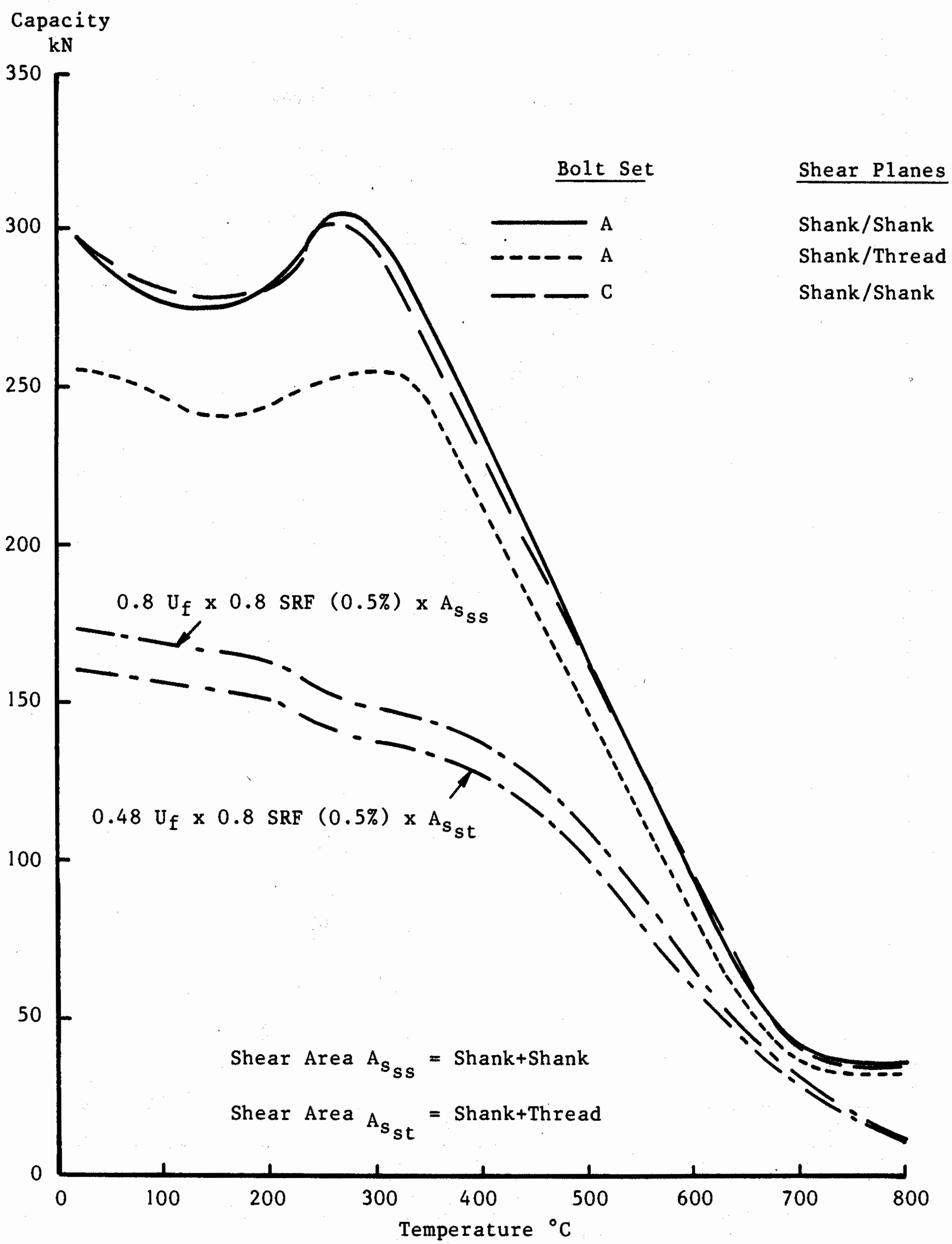
SHEAR FAILURES WITH BOTH SHEAR PLANES ACTING THROUGH THE SHANK

FIG. 16



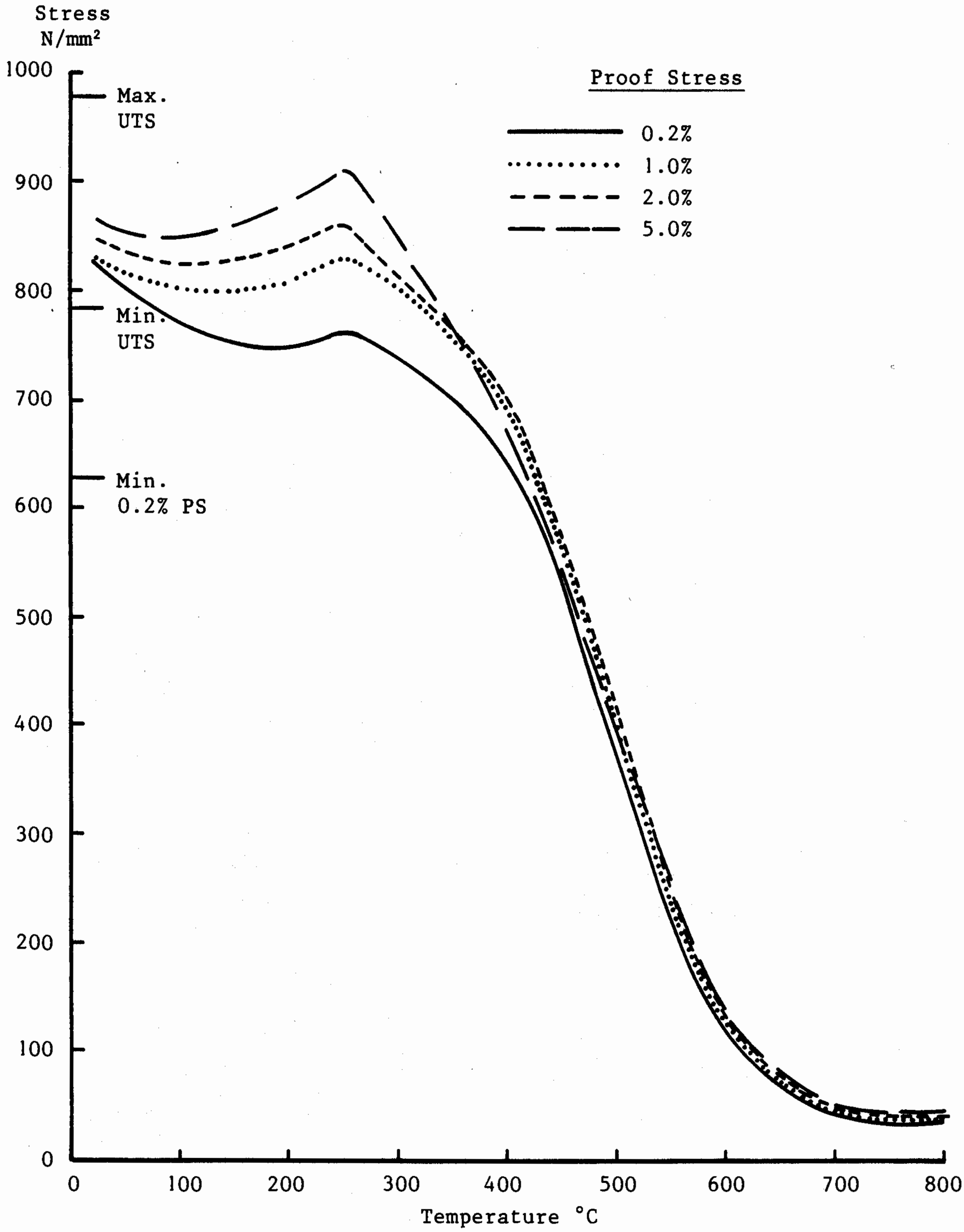
SHEAR FAILURES WITH ONE OF THE SHEAR PLANES ACTING THROUGH THE THREAD

FIG. 17



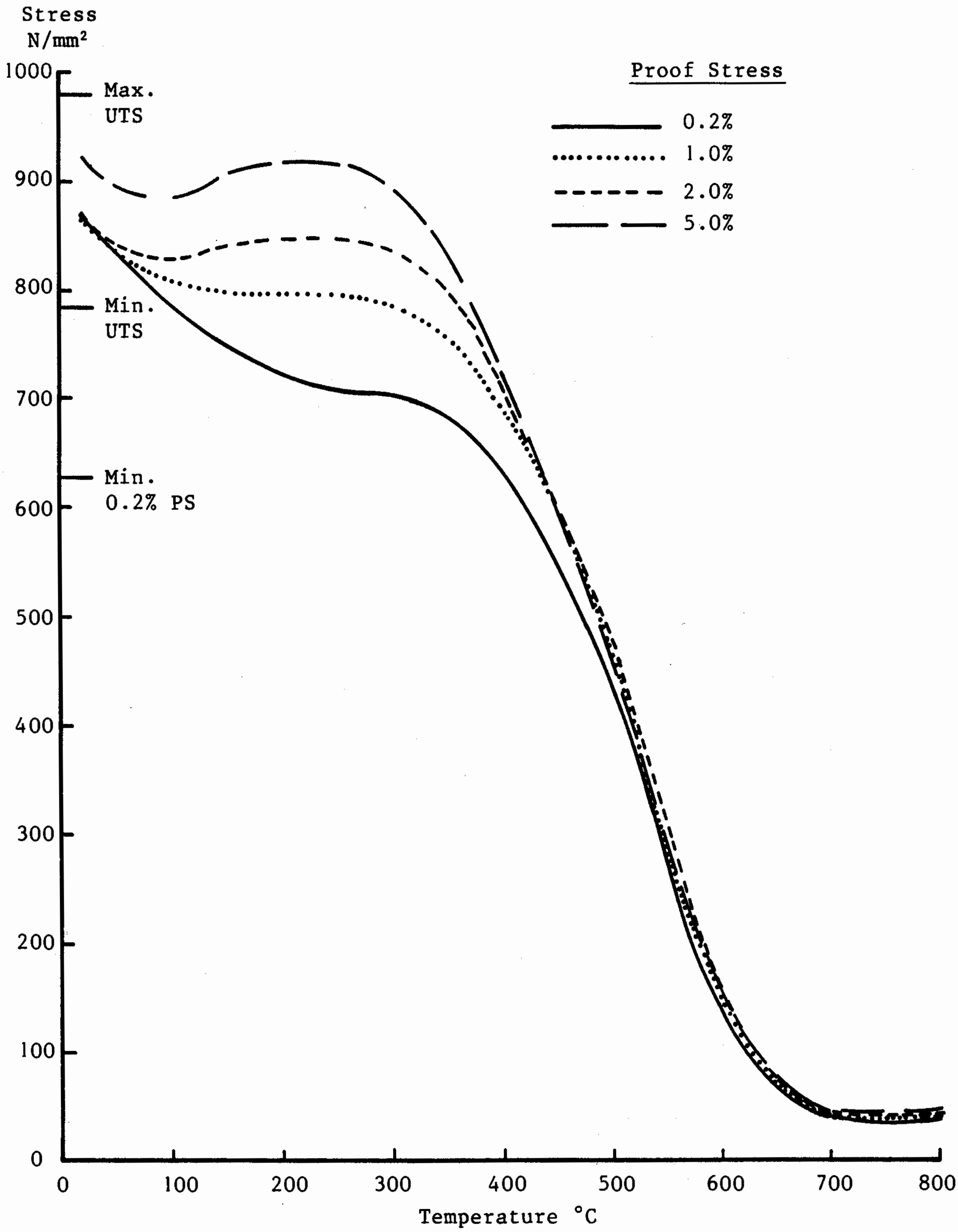
COMPARISON BETWEEN THE FIRE LIMIT STATE DESIGN CURVES AND THE CAPACITY OF GRADE 8.8 BOLTS IN DOUBLE SHEAR NORMALISED WITH RESPECT TO MINIMUM STRENGTH AND DIMENSIONAL TOLERANCES

FIG. 18 (R3/8806)



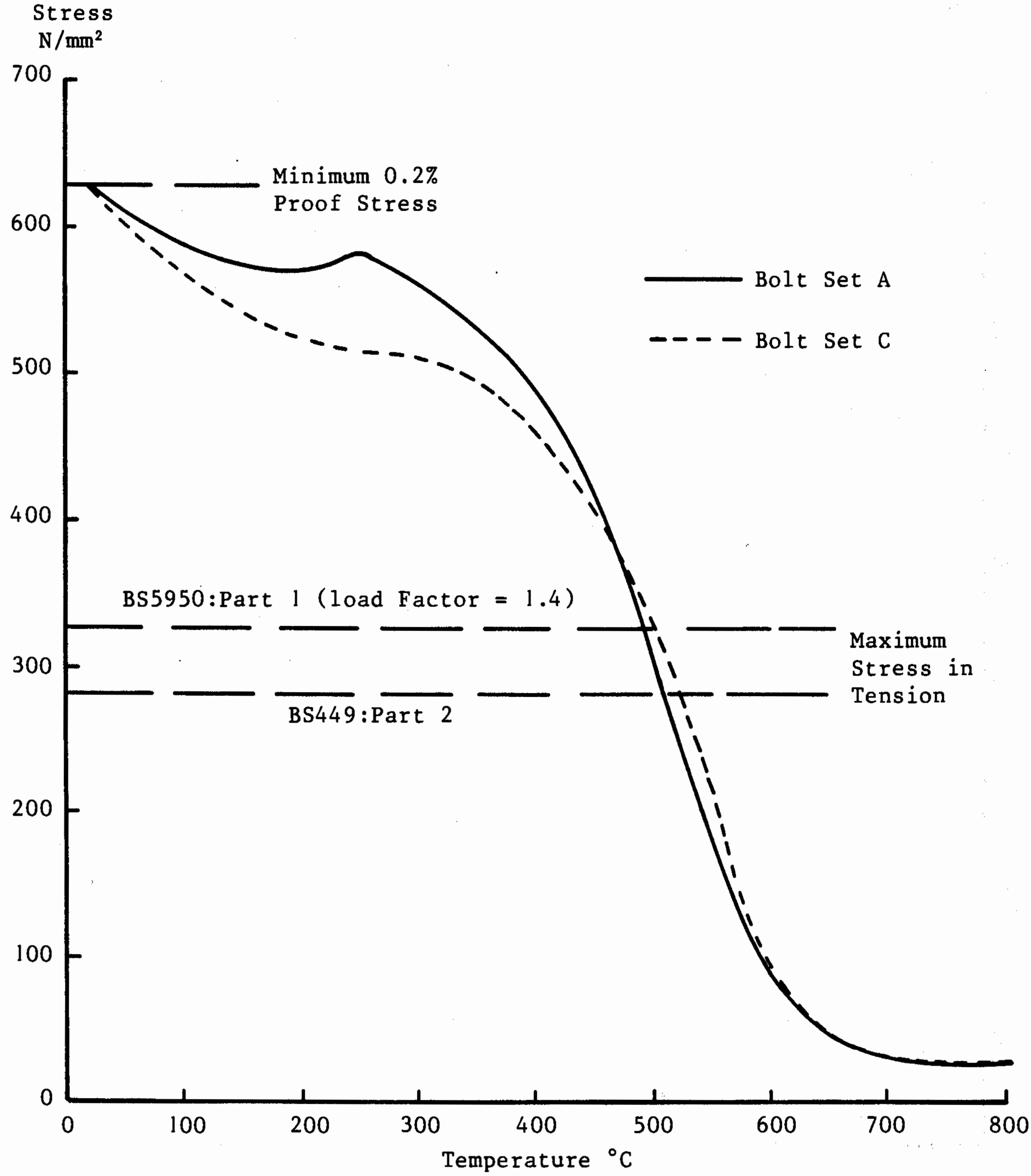
BEHAVIOUR OF HIGH STRENGTH GRADE 8.8 BOLT MATERIAL AT ELEVATED TEMPERATURES (BOLT SET A)

FIG. 19 (R3/8807)



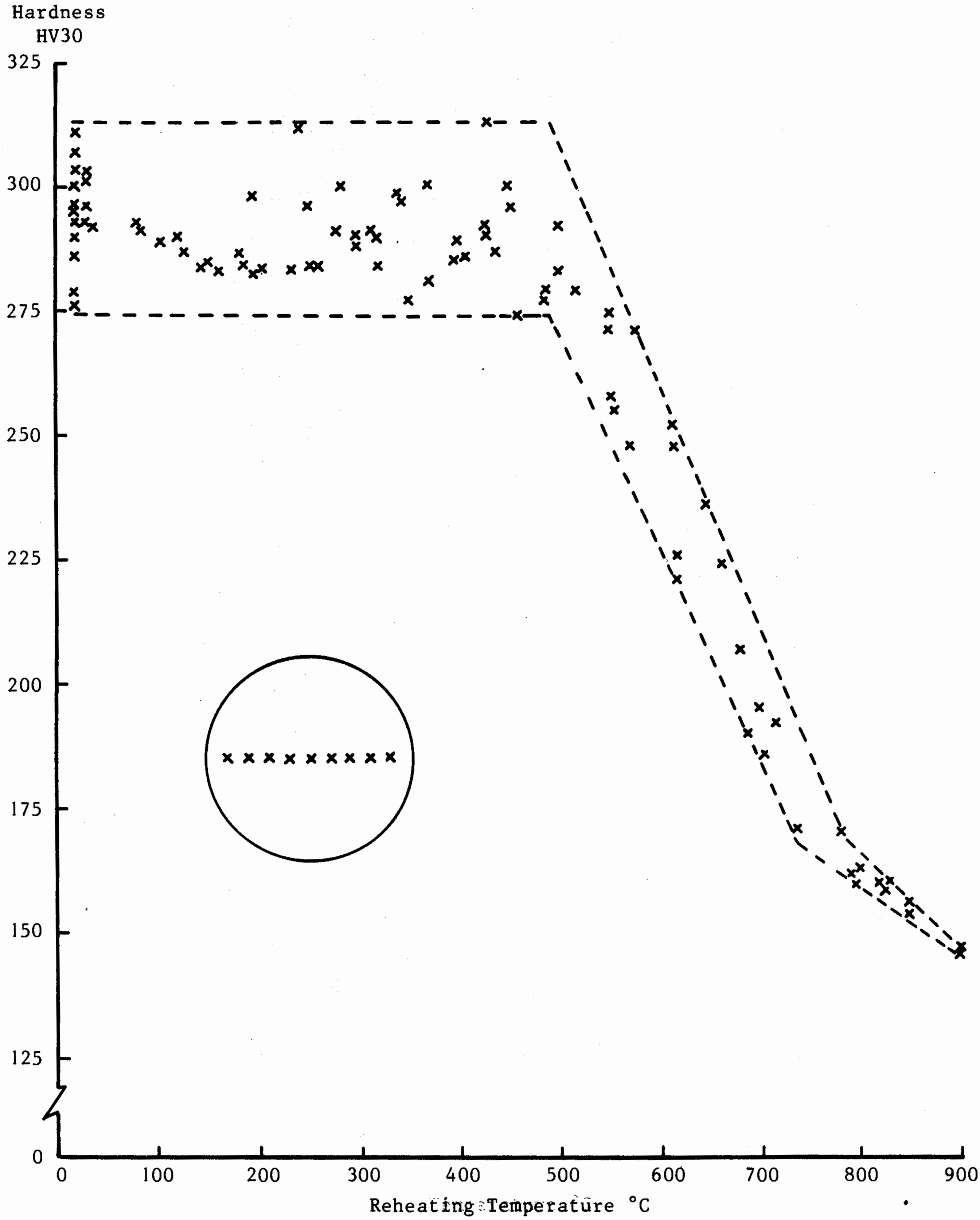
BEHAVIOUR OF HIGH STRENGTH GRADE 8.8 BOLT MATERIAL AT ELEVATED TEMPERATURES (BOLT SET C)

FIG. 20 (R3/8808)



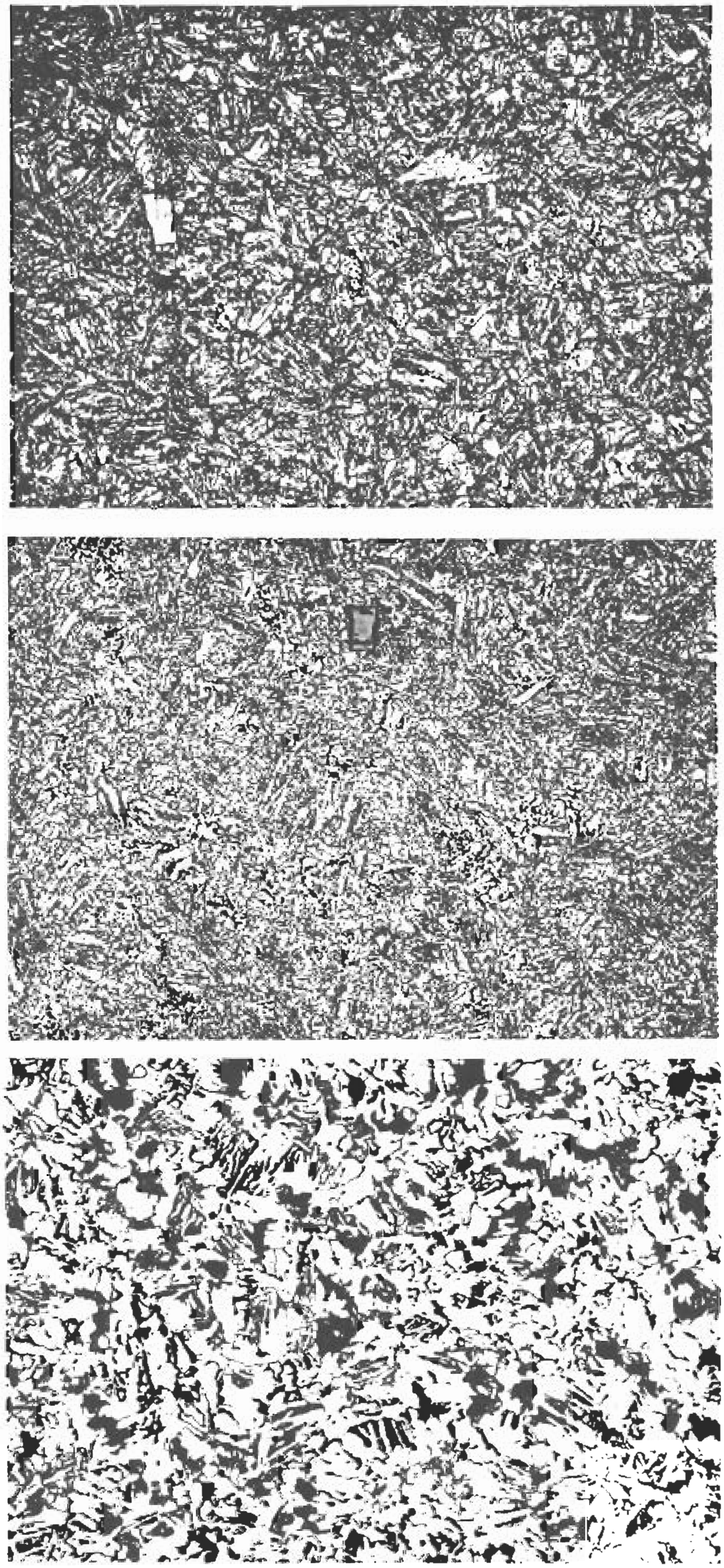
VARIATION OF THE 0.2% PROOF STRESS WITH TEMPERATURE FOR GRADE 8.8 BOLT MATERIAL NORMALISED WITH RESPECT TO THE MINIMUM SPECIFIED VALUE

FIG. 21
(R3/880



RESIDUAL HARDNESS OF GRADE 8.8 BOLTS (BOLT SET A)

FIG. 22
(R3/8810)



As-Received

x 500 (a)

700°C

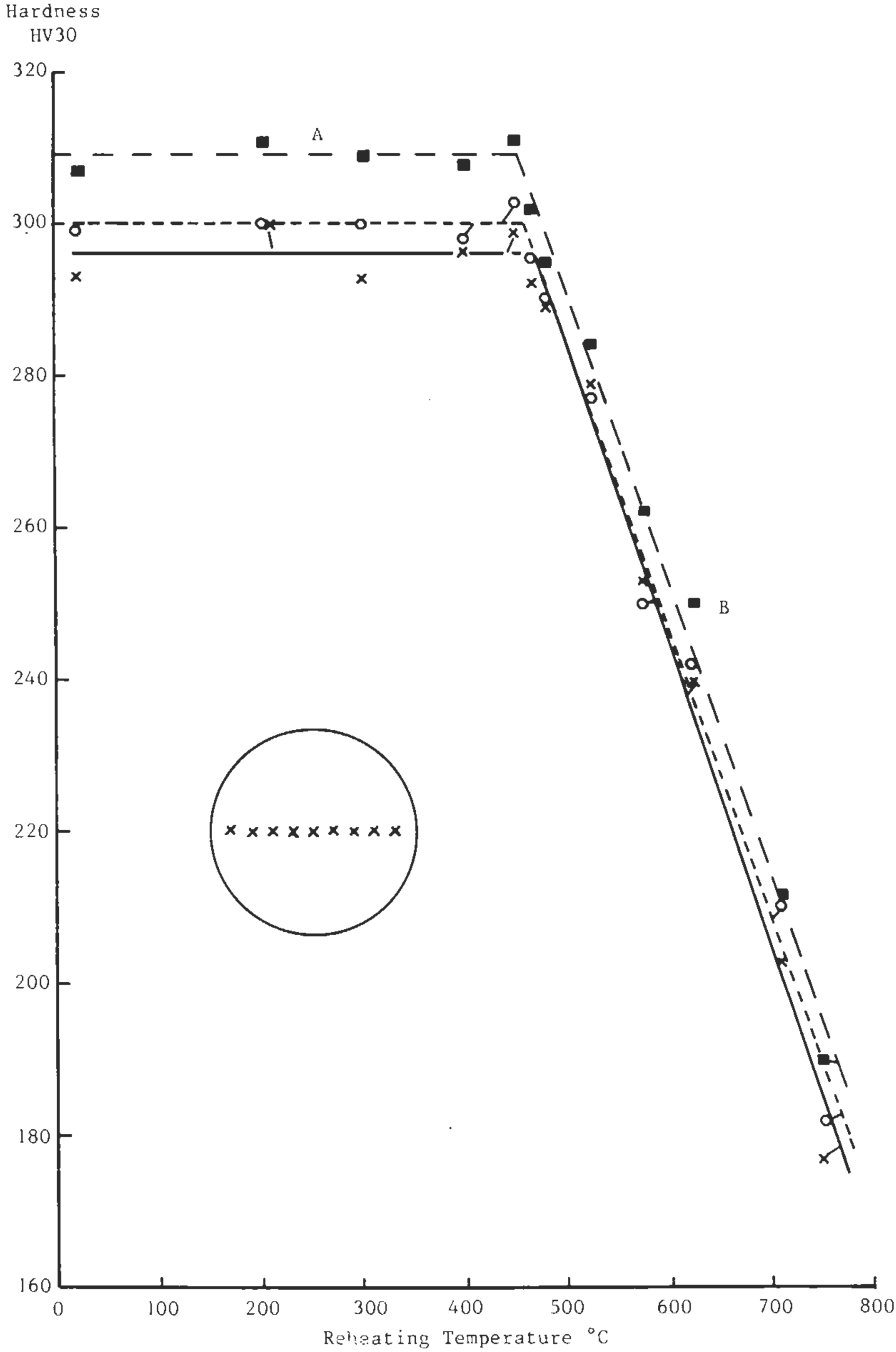
x 500 (b)

800°C

x 500 (c)

MICROSTRUCTURAL CHANGES IN HIGH STRENGTH GRADE 8.8 BOLTS AT ELEVATED TEMPERATURES

FIG. 23



RESIDUAL HARDNESS OF THREE INDIVIDUAL GRADE 8.8 BOLTS (BOLT SET A)

FIG. 24 (R3/8811)