Grade 500E Reinforcing Steel

Tests on Micro-alloy and Quenched and Tempered samples available in New Zealand.

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1. Background

Grade 500E reinforcing steel was introduced to the NZ market with the publication of AS/NZS 4671 in 2001, effectively replacing Grade 430.

Until 2006, most of the steel supplied to the New Zealand market has been micro alloy (MA) from Pacific Steel with imported quenched and tempered (QT) and MA steels making up the balance.

QT steels achieve their strength and ductility through the quenching and tempering process whereas MA steels achieve this through the additions of trace elements such as vanadium or titanium.

In 2006 Pacific Steel started manufacturing QT steel so now there is one domestic supplier producing both the MA and QT variants of Grade 500E steel, plus one importer, Nauhria Reinforcing Limited supplying QT steel from Singapore and another importer, Euro Corp, supplying MA steel from Malaysia These three suppliers dominate the market. The Department has insisted that all three steel suppliers have well-documented and adequate quality assurance processes so that reinforcing steel incorporated into buildings can be shown to comply with *AS/NZS 4671:2001 Steel reinforcing materials*. *All submissions showed that products complied with AS/NZS 4671 and gave reasonable confidence that they would continue to do so.*

In 2003 Dr Barry Davidson of the University of Auckland raised concerns about the suitability of Grade 500E reinforcing steel because of failure of bars in a laboratory experiment. The exact circumstances have not been reported in any satisfactory detail, but the problems were believed to have been caused by tack welds on the main bars, which were Pacific Steel Grade 500E MA.

In 2004, in response to Dr Davidson's concerns the Department launched an investigation into Grade 500E reinforcing to check its fitness for purpose. This investigation consisted of:

(a) A review of reported failures referred to Pacific Steel followed by a special survey of ACENZ members. This survey revealed very few reported failures or incidents. Most failures were the result of mishandling rather than inherent weakness of the material and frequently were the result of bending bars too tightly or re-bending them.

(b) Physical testing of four Grade 500E products available on the market at the time – Pacific steel MA and three imported QT materials. The aim of the tests was to check that the material complied with NZ Standards and to identify any serious concerns. Although there were some individual test results marginally below requirements, these did not constitute non-compliance of the material. No serious concerns resulted but engineers were urged to satisfy themselves of the compliance of the steel used in their projects, regardless of the source or manufacturing process.

(c) A report prepared for the Department by Beca Consultants on the adequacy and compatibility of the various Standards covering the manufacture, design, welding and handling of Grade 500E steel [1]. No serious incompatibilities or inadequacies were found but the report highlighted the need for research into safe bend diameters for Grade 500E as referred to below.

The Department's investigation resulted in a Report published in July 2005 [2]. Action addressing the problems identified in the Report, and its recommendations, was initiated by the Department and other industry organisations in the 18 months prior to publication of the report.

The investigation indicated that the industry's knowledge and understanding of Grade 500E was limited. Many engineers did not know:

- that alternative methods of manufacture were being used. (MA and QT)
- that imported reinforcing steel was being marketed as Grade 500E
- the properties of Grade 500E reinforcing or the limitations on handling, fabrication, bending, re-bending, welding, galvanising and threading.

The DBH Report recommended the following actions;

- General education of the industry on the properties of Grade 500E and its limitations and benefits
- Advice and alerts to industry about limitations and benefits of the product and the variation to be expected in the manufacturing process, suppliers, bar markings and weldability
- Research to provide better information on key issues.
- Specific advice to fabricators, constructors and designers on the need for care in handling, or fabricating, Grade 500E.
- Amendments to New Zealand Standards including information about the limitations regarding Grade 500E steel.

Specifically, the Beca report included a recommendation that "*minimum bar bending diameters specified in NZS3101 be reviewed to ensure adequate margin against fracture of Grade 500E steel*". In response the Department commissioned special tests which are ongoing. Details of this project and the results so far are given below.

Grade 500E, New Zealand Standards, Compliance Documents BI/VM1

During the investigation the Department worked closely with New Zealand Standards and in March 2004 NZ Standards published amendments to *NZS 3101: Part 1:1995 The Design of Concrete Structures* and *NZS 3109:1997 Concrete Construction*. These amendments introduced *AS/NZS 4671;2001 Steel reinforcing materials* identified MA and QT steels and specifically covered the handling limitations (bending, re-bending, welding, galvanising and threading) of these two types of steel. The same provisions have been incorporated in NZS 3101:2006.
In March 2005 the Department cited the above amendments to these Standards and referenced them in the compliance document B1/ VM1.

Publicity about Grade 500E

Following a series of Seminars in September 2003, the Cement & Concrete Association of NZ (CCANZ) issued an *Information Bulletin IB79 "Recommended Industry Practice on Bending and Re-bending of Reinforcing Bars"* in December 2004. The seminars and bulletin did much to inform the industry about Grade 500E steel.

The Structural Engineers Society New Zealand (SESOC) has been active in the investigation and debate about Grade 500E reinforcing. Articles on Grade 500E have been published in its Journals of April 2001, April 2002, April 2004 and September 2005.

To help inform the industry the Department has issued the following documents:

- *Practice Advisory 1: Bend the bar not the rules"* was issued in December 2004 and amended and re-issued in June 2005.
- *Practice Advisory 7: Use with care, Grade 500E reinforcing steel in New Zealand"* was issued in July 2005.
- A wall chart *Reinforcing Steel in New Zealand- A quick guide for designers, building consent authorities and contractors* was issued in June 2005. Most of the information on this chart relates to Grade 500E. A minor but significant amendment to this wall chart was issued in March 2006. An amended chart is due for completion in 2008.
- The *Report on Grade 500E Steel Reinforcement* was published in August 2005 and posted on the Departmental website. It was also notified via the Department's email service BC Update.

In 2006 the Department, in association with the Cement & Concrete Association of NZ (CCANZ), produced and distributed over 6000 *bendometers*, a simple device developed by the Department to promote the correct bending of reinforcement.

A gratifying outcome of this publicity was that many small builders were concerned to discover that they had unwittingly been bending bars too tightly. Often this was simply because the bar bender they bought from their local building supply merchant has a fixed mandrel which results in a 2D bend on a 16mm bar. They were not aware that a range of former diameters is required to cover all bar sizes.

The bendometers and other publicity appear to have helped to improve compliance of the initial bend. However, the Department is not convinced that the instances of re-bending of Grade 500E reinforcement have reduced significantly.

Ongoing debate

There has been a great deal of debate and concern in the profession about Grade 500E even after the issue of information to the industry. Much of it has focused on the imported steels and the QT variant of Grade 500E. Some consultants specify that only the MA variant be used in the mistaken belief that QT bars are brittle and can easily fracture on re-bending. (The research into bend diameters described below has shown that both MA and QT steels available in New Zealand have performed similarly in tests in which they were cold bent and then straightened rapidly. In this limited number of tests QT bars performed marginally better than the MA bars.)

2. *Bend diameter research project*

Background

The following table compiled by the Department summarises the history of required bend diameters in NZ Standards since 1970.

Table 1: Bend diameters from NZ Standards

Review of Bend Diameters for Reinforcing in Successive NZ Standards																	
		All figures are multiple of bar diameter unless noted otherwise															
Standard	**Grade**	**Bend Diameters**															
		Deformed or Plain Bars										**Stirrups and Ties**					
		6	10	12	16	20	25	32	40			10	12	16	20	24	
NZS 1900 Chapter 9.3A 1970	275		5	5	6	6	6	8	8			2	2	2	Requirement was for bend to match diameter of main bar. Figure shown is an estimate		
NZS 3101 P 1970	275		5	5	6	6	6	8	8			2	2	2			
NZS 3109 1980	275		5	5	5	5	5	6	6		Plain	2	2	2	2	2	
											Def	4	4	4	4	4	
	380		8	8	8	8	10	10	10		Plain	4	4	4			
											Def	8	8	8			
NZS 1900 Chapter 9.3 1981	275		5	5	5	5	5	6	6		Plain	2	2	2	2	2	
											Def	4	4	4	4	4	
	380		8	8	8	8	10	10	10		Plain	4	4	4			
											Def	8	8	8			
NZS3101 : 1982	275		5	5	5	5	5	6	6		Plain	2	2	2	2	2	
											Def	4	4	4	4	4	
	380		8	8	8	8	10	10	10		Plain	4	4	4	4		
											Def	8	8	8	8		
NZS 3101 1987	275		5	5	5	5	5	6	6		Plain	2	2	2	2	2	
											Def	4	4	4	4	4	
	380		8	8	8	8	10	10	10		Plain	4	4	4			
											Def	8	8	8			
NZS 3101: 1995	300		5	5	5	5	6	6	6		Plain	2	2	2	2	3	
and	430		5	5	5	5	6	6	6		Def	4	4	4	4	6	
NZS 3101: 2006	500		5	5	5	5	6	6	6								
	Galvanised		5	5	5	8	8	8	8								

This table, prepared by the Department, is reproduced from Appendix A of a report done for the Department [1] which notes:

> *Since 1970s steels with yield stresses of 430 MPa and 500 MPa have been introduced, with no revision to the minimum bend diameters when Grade 500 was introduced. Significantly this shows increases to 8 d and 10 d in 1980 for Grade 380 steel, but a reversion to tighter diameters in 1995. This coincided with the introduction of Grade 430 steel (a micro alloy steel designed to have improved ductility) to replace Grade 380 (a plain carbon steel). The*

Commentary to NZS 3101: 1995 pointed out that the bend diameters required were twice those required of the bend test in NZS 3402. In 2001, NZS 3402 was replaced by AS/NZS 4671 and required diameters for the bend test were increased. No changes to the required bend diameters were made when Grade 500E steel was introduced. The report on Standards has been sent to Standards New Zealand for consideration and includes a recommendation to review the minimum bend diameters for reinforcing steel.

No definitive answers to these questions were evident from recent enquiries and research. The relationship between yield stress and an acceptable bending strain could not be clearly defined. Work is needed to provide a definitive relationship that can be used to determine suitable minimum bending diameters for steels of various types and yield stress levels.

The report included a recommendation that "*minimum bar bending diameters specified in NZS3101 be reviewed to ensure adequate margin against fracture of Grade 500E steel*".

It was recognised that similar concerns had been expressed in the 1970's when Grade 380 steel (HY60) was introduced. At that time studies showed that the strains produced during bending of a deformed reinforcing bar are very high and near the limit of capability of the material. Minimum bend diameters were increased as a result of studies of the strains induced and the metallurgical properties of the steel.

The key questions are what, if any, adjustments to allowable bending diameters should be made to allow for the increase in yield stress to 500 MPa from 430 MPa or Grade 380? If adjustments should be made, what is the basis for making a change?

In early 2006 DBH initiated an investigation into safe bend diameters (SBD's) specified in NZS 3101 and NZS 3109 and the manufacturer's test specified in AS/NZS 4671. On behalf of the Department, independent testing was undertaken by Quest Reliability LLC, formerly MPT Solutions, which used to be the Metallurgical Division of DSIR.

The objectives of the research were to:

(a) Verify that the bend diameters specified by both NZS 3101 and NZS 3109 are appropriate

(b) Verify that the manufacturer's test specified in AS/NZS 4671 is satisfactory for Grade 500E steel.

In addition, the tests are aimed at demonstrating that Grade 500E bars cold bent to complying diameters will perform satisfactorily in an earthquake.

Bending of bars causes permanent strains and reduces the ductility available. It is generally believed that the higher the yield stress of a reinforcing steel the lower the overall ductility. However, no meaningful relationship exists between yield stress and ductility.

Research in the 1980's, which was provoked by similar concerns about Grade 380 after it was introduced in 1980, identified that strain aging embrittlement was a problem caused by nitrogen. MA steels use trace elements such as titanium or vanadium to provide strength and toughness. The research established that bending raised the ductile to brittle transition temperature (DBTT) of steel, the temperature below which a steel will behave in a brittle, rather than in a ductile manner. Hence a straight bar may have a transition temperature of -20°C whereas after bending to a specific diameter this temperature may rise to -10°C. Thus if a building has some bent bars of this assumed steel and the temperature drops to say, -8°C and along comes an earthquake then the building, or least the particular member containing the bent bar, would not exhibit the expected ductility and could behave in a brittle manner.

This raises some interesting questions about the general and extreme weather conditions in New Zealand. The lowest recorded temperature in New Zealand is -20°C in Ophir in Central Otago which is a relatively short distance inland from Mosgiel and Dunedin. No doubt this sort of temperature and possibly lower, occur regularly in the mountains but it is hardly reasonable to set the criteria for NZ on the basis of a few ski lodges. There is also the question of how cold the bars get within a reinforced concrete column or beam in relation to the outside air temperature. Concrete is a poor insulator but cold tends to be "snaps" in New Zealand rather than sustained. In most parts of New Zealand anything below zero is relatively infrequent so if a bent reinforcing bar is ductile above -10°C it should perform satisfactorily in most places in New Zealand. Very few normal structures are likely to require design for -20°C, but cold stores could be exceptions. In these cases it will be particularly important to recognise the brittle behaviour of Grade 500E reinforcing steel at low temperatures. Steel that needs to be ductile at temperatures below minus 10^{o}C should be verified by test as having the necessary ductility at the design temperature.

Test description

A typical test sample is bent to the shape shown, aged at 100°C for one hour then cooled to the required test temperatures. The test consists of pulling the bar straight at a strain rate similar to that of an earthquake. No strain measurements are taken. The type of performance, ductile or brittle is recorded together with its location along the bar.

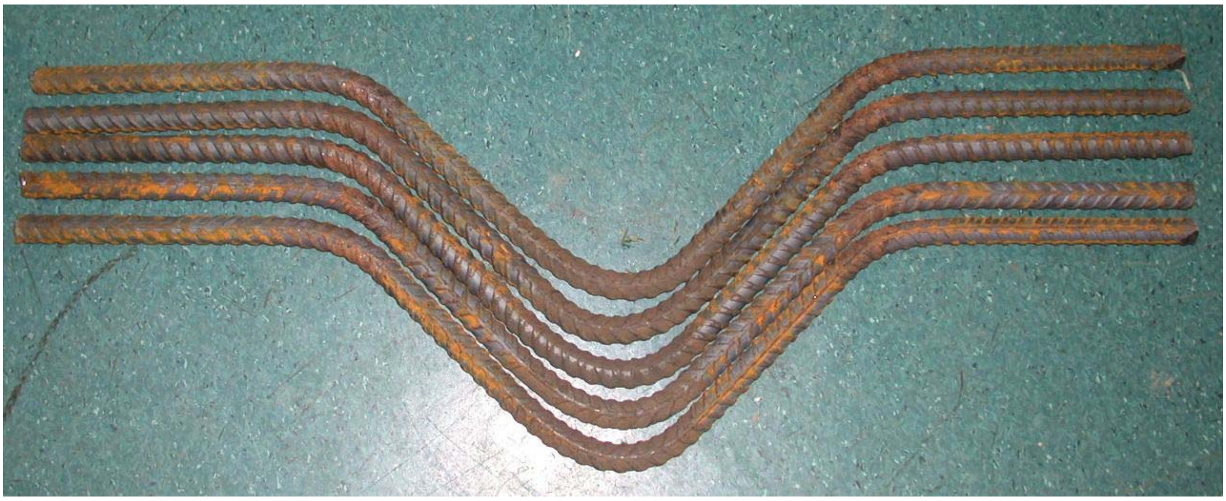

Figure 1: Some of the 20mm diameter test specimens before straightening.

If bars behave in a ductile manner in these tests then we can have reasonable confidence that the Grade 500E bars will be satisfactory in normal service. These tests are very severe compared with likely real life situations especially for larger bars.

Four variants of Grade 500E were tested;

- MA and QT from Pacific Steel,
- QT supplied by Nauhria Building Supplies and manufactured by NatSteel Ltd of Singapore (now a subsidiary of Tata Steel of India) and
- MA supplied by Euro Corp and manufactured by Amsteel of Malaysia (Until 2005 Euro Corp imported a QT variant).

All are manufactured to AS/NZS 4671: 2001 which allows Grade 500E to be manufactured in diameters from 8mm to 40mm. Six sizes are readily available in NZ; 10, 12, 16, 20, 25 and 32mm diameter.

Initially the Department planned a full matrix of tests – all diameters, all 4 sources of supply and at a range of temperatures. Further consideration led to a staged approach to reduce the number of tests without significant loss of relevant information. The need for further tests was reviewed as testing progressed.

The Phase I tests were aimed at establishing the transition temperature and the likely behaviour over the range of bar sizes and over a bend diameter range of 2D to 6D.

Bars up to and including 16mm diameter passed the test in Phase 1, so Phase II tests were confined to 20, 25 and 32mm diameter bars from all 4 supply sources.

5. *Results of Test Programme*

Test results are presented in the following tables. Each table shows the number of tests done, and the number of brittle fractures for the combinations of bar diameter, bend diameter and temperature.

It is important to note the limited number of tests carried out and to remember that the test demanded much more of the bars than would normally be asked of them in practice.

However, the tests do give an indication of general ductility of the various bars under these conditions.

The basic purpose of the tests was to verify that the minimum bend diameters specified in NZS 3101 and NZS 3109 are adequate. There are clearly gaps in the testing regime, but although the tests are limited in number, it appears from the results that the bend diameters are adequate provided temperatures in service are not below minus 10°C. On the other hand, the tests do not indicate any justification for allowing tighter bends.

Table 2: Summary of Results for all bars

Results from Quest / MPT tests - **All bars (MA and QT)**

Number of bars showing brittle fracture / number tested

10mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5	0 / 1	0 / 1					
6							

12mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5	0 / 2	0 / 2					
6							

16mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5	0 / 2	0 / 2					
6							

20mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2		1 / 2					
3		0 / 2	7 / 8	5 / 8			
4		0 / 2	0 / 8	0 / 6			
5	0 / 4	1 / 6	0 / 2	0 / 2	0 / 2		
6							

25mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3			7 / 8	6 / 8			
4			7 / 8	6 / 8			
5					3 / 12	2 / 10	2 / 10
6	0 / 2	1 / 1			0 / 8	0 / 8	0 / 8

32mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3			8 / 8	8 / 8			
4			4 / 8	4 / 8			
5					1 / 8	1 / 8	0 / 8
6	1 / 2				0 / 8	0 / 8	0 / 8

100% Brittle fractures
Mixed brittle and ductile fractures
100% Ductile fractures

235 Tests total
75 Brittle fractures

Table 3a: Summary of Results for MA bars

Results from Quest / MPT tests - **All MA bars**

Number of bars showing brittle fracture / number tested

10mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5		0 / 1					
6							

12mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5	0 / 1	0 / 1					
6							

16mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5	0 / 1	0 / 1					
6							

20mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2		1 / 1					
3		0 / 1	3 / 4	1 / 4			
4		0 / 1	0 / 4	0 / 4			
5	0 / 2	0 / 3	0 / 1	0 / 1	0 / 1		
6							

25mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3			4 / 4	4 / 4			
4			4 / 4	4 / 4			
5					3 / 8	2 / 6	2 / 6
6	0 / 1	1 / 1			0 / 4	0 / 4	0 / 4

32mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3			4 / 4	4 / 4			
4			2 / 4	2 / 4			
5					1 / 4	0 / 4	0 / 4
6	1 / 1				0 / 4	0 / 4	0 / 4

100% Brittle fractures
Mixed brittle and ductile fractures
100% Ductile fractures

123 Tests total
43 Brittle fractures

Table 3b: Summary of Results for MA bars – Pacific Steel

Results from Quest / MPT tests - **MA bars - Pacific Steel only**

Number of bars showing brittle fracture / number tested

10mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5							
6							

12mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5	0 / 1						
6							

16mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5	0 / 1						
6							

20mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2		1 / 1					
3		0 / 1	1 / 2	1 / 2			
4		0 / 1	0 / 2	0 / 2			
5	0 / 2	0 / 2	0 / 1	0 / 1	0 / 1		
6							

25mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3			2 / 2	2 / 2			
4			2 / 2	2 / 2			
5					1 / 2	0 / 2	0 / 2
6	0 / 1				0 / 2	0 / 2	0 / 2

32mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3			2 / 2	2 / 2			
4			0 / 2	0 / 2			
5					0 / 2	0 / 2	0 / 2
6	1 / 1				0 / 2	0 / 2	0 / 2

- Red: 100% Brittle fractures
- Yellow: Mixed brittle and ductile fractures
- Green: 100% Ductile fractures

62 Tests total
17 Brittle fractures

Table 3c: Summary of Results for MA bars – Euro Corp

Results from Quest / MPT tests - **MA bars - Eurocorp only**

Number of bars showing brittle fracture / number tested

10mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5		0 / 1					
6							

12mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5		0 / 1					
6							

16mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5		0 / 1					
6							

20mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3			2 / 2	0 / 2			
4			0 / 2	0 / 2			
5		0 / 1					
6							

25mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3			2 / 2	2 / 2			
4			2 / 2	2 / 2			
5					2 / 6	2 / 4	2 / 4
6		1 / 1			0 / 2	0 / 2	0 / 2

32mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3			2 / 2	2 / 2			
4			2 / 2	2 / 2			
5					1 / 2	0 / 2	0 / 2
6					0 / 2	0 / 2	0 / 2

- Red: 100% Brittle fractures
- Yellow: Mixed brittle and ductile fractures
- Green: 100% Ductile fractures

61 Tests total
26 Brittle fractures

Table 4a: Summary of Results for QT bars

Results from Quest / MPT tests -**QT bars**

Number of bars showing brittle fracture / number tested

10mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5	0 / 1						
6							

12mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5	0 / 1	0 / 1					
6							

16mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3							
4							
5	0 / 1	0 / 1					
6							

20mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2		0 / 1					
3		0 / 1	4 / 4	4 / 4			
4		0 / 1	0 / 4	0 / 2			
5	0 / 2	1 / 3	0 / 1	0 / 1	0 / 1		
6							

25mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3			3 / 4	2 / 4			
4			3 / 4	2 / 4			
5					0 / 4	0 / 4	0 / 4
6	0 / 1				0 / 4	0 / 4	0 / 4

32mm bar

Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2							
3			4 / 4	4 / 4			
4			2 / 4	2 / 4			
5					0 / 4	1 / 4	0 / 4
6	0 / 1				0 / 4	0 / 4	0 / 4

- Red: 100% Brittle fractures
- Yellow: Mixed brittle and ductile fractures
- Green: 100% Ductile fractures

112 Tests total
32 Brittle fractures

Table 4b: Summary of Results for QT bars – Pacific Steel

Results from Quest / MPT tests -**QT bars - Pacific Steel only**

Number of bars showing brittle fracture / number tested																							
10mm bar								**12mm bar**								**16mm bar**							
Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C	Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C	Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2								2								2							
3								3								3							
4								4								4							
5								5		0 / 1						5		0 / 1					
6								6								6							
20mm bar								**25mm bar**								**32mm bar**							
Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C	Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C	Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2								2								2							
3			2 / 2	2 / 2				3			2 / 2	1 / 2				3			2 / 2	2 / 2			
4			0 / 2					4			2 / 2	2 / 2				4			2 / 2	2 / 2			
5		1 / 1						5					0 / 2	0 / 2	0 / 2	5					0 / 2	1 / 2	0 / 2
6								6					0 / 2	0 / 2	0 / 2	6					0 / 2	0 / 2	0 / 2

100% Brittle fractures
Mixed brittle and ductile fractures
100% Ductile fractures

49	Tests total
21	Brittle fractures

Table 4c: Summary of Results for QT bars – Nauhria Reinforcing

Results from Quest / MPT tests -**QT bars - Nauhria only**

Number of bars showing brittle fracture / number tested																							
10mm bar								**12mm bar**								**16mm bar**							
Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C	Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C	Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2								2								2							
3								3								3							
4								4								4							
5	0 / 1							5	0 / 1							5	0 / 1						
6								6								6							
20mm bar								**25mm bar**								**32mm bar**							
Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C	Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C	Bend dia	-30°C	-25°C	-20°C	-15°C	-10°C	0°C	10°C
2		0 / 1						2								2							
3		0 / 1	2 / 2	2 / 2				3			1 / 2	1 / 2				3			2 / 2	2 / 2			
4		0 / 1	0 / 2	0 / 2				4			1 / 2	0 / 2				4			0 / 2	0 / 2			
5	0 / 2	0 / 2	0 / 1	0 / 1	0 / 1			5					0 / 2	0 / 2	0 / 2	5					0 / 2	0 / 2	0 / 2
6								6	0 / 1				0 / 2	0 / 2	0 / 2	6	0 / 1				0 / 2	0 / 2	0 / 2

100% Brittle fractures
Mixed brittle and ductile fractures
100% Ductile fractures

63	Tests total
11	Brittle fractures

Phase I Tests

The first test set, Phase Ia, tried to establish the transition temperature and involved 20 diameter bars from two sources; Pacific Steel MA and Nauhria/Natsteel QT, all bent to NZS 3101 safe bend diameter 5D, and tested at temperatures ranging from -10°C to -30°C in 5 degree increments. The second test set, Phase Ib, involved a range of six bar diameters, 10mm to 32mm, bent to 5d or 6d in accordance with NZS 3101 and tested at -25°C and -30°C. The intention was to conduct 48 tests (6 bar diameters x 4 suppliers x 2 bend diameters) but because of supply limitations 38 tests were conducted.

The third test set, Phase Ic, involved 20mm diameter bars supplied by Pacific Steel MA and Nauhria/Natsteel QT bent to a range of bend diameters from 2D to 5D and tested at -25°C, a total of 8 tests. A bar bend diameter of 5D is the NZS 3101 requirement.

Over all samples, ductile fractures typically occurred in the straight section, reflecting the strain hardening at and near the bend. Brittle fractures generally occurred in the 90° bend.

Phase II Tests

Phase I tests indicated that 10, 12 and 16mm Grade 500E, both MA and QT passed the test if bent in accordance with NZS 3101.

Phase II tests were therefore confined to 20, 25 and 32mm diameter bars, from all supply sources. (MA and QT from Pacific Steel, QT from Nauhria/NatSteel and MA from Euro Corp. Two samples of each size from each supplier were bent to 3D and 4D and tested at -20°C and -15°C. Hence there were a total of 96 tests.

Tests showed that the 20mm bars bent to 4D fractured in a ductile manner but the 25 and 32mm bars bent to 4D mostly did not. Refer to Tables 1, 2 and 3 for details.

In reviewing Phase II results Department staff, together with the technical staff from Quest, concluded that it was hardly surprising that the 25 and 32mm bars were showing brittle behaviours in what can only be described as very severe tests. They were being bent to very tight diameters of 3D and 4D compared with NZS 3101 requirement of 6D and then being subject to what was effectively a rapid re-bend test at very low temperatures by normal New Zealand standards.

These larger bar sizes cannot be re-bent on site. Hence it was decided that Phase III would modify the demands on the bars to a more realistic level.

Phase III tests

The Phase III tests included samples from all sources of supply:

- Phase IIIa Bend bars through 180° around a 4D pin and check visually for cracks
- Phase IIIb Dynamic tests per Phases I and II for both 25 and 32mm bars bent to 5D and 6D and tested at -10°C, 0°C, +10°C, a total of 96 tests.

The results of the Phase IIIb tests indicate the range of temperatures and bend diameters that allow the bars to fracture in a ductile manner. Out of 96 tests, there were nine brittle fractures. Seven of these were on 25mm MA bar bent to 5D, rather than the 6D specified in the standard. The same bars, when bent to 6D, all behaved in a ductile manner. Six of the seven were from one source and six further samples of 25mm MA bar were obtained and bent to slightly tighter than 5D. In this re-test, all behaved in a ductile manner.

Quest Reliability, the testing organisation that carried out the tests, was asked to investigate possible reasons for the inconsistent behaviour. This included chemical analysis, metallurgical examination and hardness tests on MA bars from Euro Corp and Pacific Steel. With such a small sample and limited investigation it was difficult to draw firm conclusions from this investigation. However, Quest Reliability reported [6] that it appeared that the lack of a rounded transition between the deformation rib face and the bar may have influenced the development of spring-back cracks and brittle breaks during the tests.
AS/NZS 4671, while requiring a rounded transition, does not specify a dimension to define what is meant by “rounded”. Refer Figure 1 below.

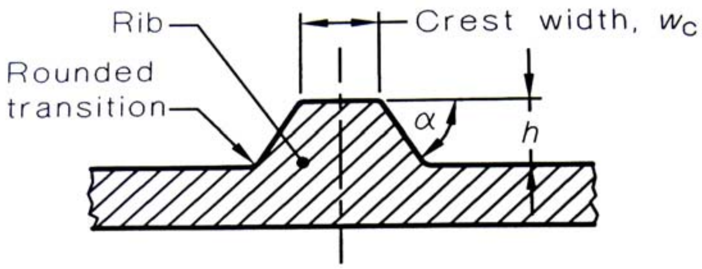

Figure 1: Extract from AS/NZS 4671 showing requirement for rounded transition

Ductile performance in these tests indicates that the relevant Grade 500E bars are capable of maintaining ductility after single cold bending. However, brittle fractures indicate only that the relevant bar / bend diameter combination is not tolerant of this severe straightening action. Brittle fractures do not indicate non-compliance with the standard.

6. *Conclusions and Questions*

Caution is needed in making general interpretations from such a limited number and range of tests, but the following conclusions can be drawn:

(a) The Grade 500E samples from the three sources of supply, and bent to the required bend diameter, have performed satisfactorily in these tests, especially the 10, 12, 16 and 20mm bars.

(b) Although there were anomalous results for some 25mm MA bars, there is little in these tests to separate the performance of MA and QT steels cold bent to the same diameters and tested under the same conditions.

(c) Temperature has a significant effect on ductility. For the smaller bars up to 20mm diameter, this is not an issue for most applications in New Zealand. It is unlikely to be an issue for larger bars bent in accordance with New Zealand Standards, provided the in-service temperatures are above -10°C

(d) A cautionary note is needed in NZS 3109, in NZS 3101 and generally to industry that the ductility of Grade 500E reinforcement, like any high strength steel, reduces markedly at very low temperatures.

(e) No reason has emerged that would require modification of the bend / re-bend tests prescribed in AS/NZS 4671.

(f) No reason emerged that would require modification to the minimum bend diameters specified in NZS 3101.

(g) Bending does reduce ductile capacity, and the tighter the bend the more ductility is lost. Where the tests show ductile behaviour in these tests, there is every confidence that bars bent to similar diameters will exhibit adequate ductility in service above minus 10^{o}C. However, this conclusion must be tempered with the fact that the range of samples in the test programme was very limited.

(h) **Re-bending of Grade 500E reinforcing steel must not be permitted.** The condition of a re-bent bars in a real building will be similar to that of the test samples *at the end of the test* – they will have been cold bent and re-bent (or straightened). If further ductility is demanded of that bar, there is a high likelihood that its capacity for further ductile deformation will be limited or non-existent. This applies equally to both MA and QT bars when bent cold. (Manufacturers of Grade 500E MA point out that the material may be bent after heating provided detailed procedures are followed. The Department does not have confidence in the outcome of such procedures carried out in construction situations.)

(i) Restrictions on welding and threading as noted in Practice Advisory No 7 still apply. QT bars should not be threaded, welded or hot bent because there is a high likelihood that properties of the bar will change. Galvanising of QT bars may be acceptable if the supplier can demonstrate that the key properties required are unchanged by the process. QT reinforcing bars were shown to have ample ductility to cope with normal bending processes.

The Department strongly advises against any welding of Grade 500E reinforcement, whether MA or QT. The manufacturers and suppliers of both MA and QT material point out that welding is not detrimental when done under carefully prescribed conditions. The Department does not believe these prescribed conditions can be relied on to exist on construction sites. The range of circumstances and variables is too wide to give confidence in the result.

Even in shop conditions welding should not be relied upon without evidence that the welding produces consistent results that do not reduce the strength or ductility of the bars to below the requirements of AS/NZS 4671.

(j) Tack welding of Grade 500E reinforcing steel, both MA and QT must not be allowed. (Tack welding of any reinforcing steel can create stress concentrations and/or alter the properties of the steel.)

References

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