BETONGKONSTRUKSJONERS LIVSLØP

Et utviklingsprosjekt i samarbeid mellom offentlige byggherrer, industri og forskningsinstitutter

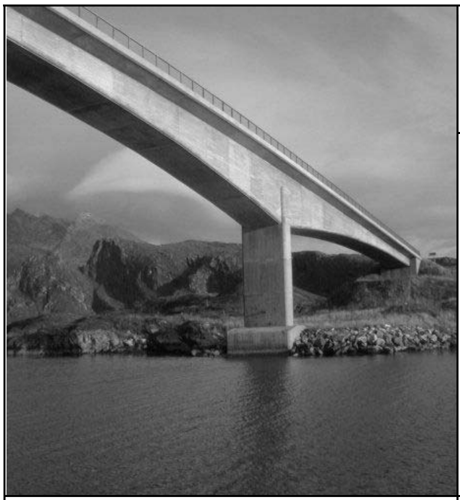
Deltakere:
Statens vegvesen (prosjektledelse), Forsvarsbygg, NORCEM A.S, Selmer Skanska AS, Sika Norge AS, Norges byggforskningsinstitutt, NTNU, SINTEF, NORUT Teknologi as

Rapport nr. 18

Heftforhold for rustfritt armeringsstål.

Aktivitet DP2 C2

Prosjektet er støttet av BA-programmet i Norges forskningsråd



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Heftforhold for rustfritt armeringsstål

Aktivitet DP2 C2

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PROSJEKTLEDERE:
Finn Fluge og Bernt Jakobsen

KORT SAMMENDRAG

For bestemmelse av heftegenskapene til rustfri armering er det utført laboratorieforsøk hvor rustfri armering sammenlignes med vanlig armering. Forsøksprogrammet omfattet uttrekksforsøk, kontroll av betongens trykkfasthet og måling av armeringens kamgeometri.

Den rustfrie armeringen var av to typer austenittisk stål, kaldtrukket stål, W 1.4401, med dimensjon ø8, ø10 og ø12 mm og varmvalset stål, W 1.4429, med dimensjon ø16 og ø25 mm.

Alle prøvene av karbonstål, samt rustfri armering med dimensjon ø8, ø16 og ø25 mm tilfredsstilte regelverkets krav til kamgeometri. De normaliserte uttrekkskreftene var høyere for rustfri armering enn for vanlig armering av karbonstål, henholdsvis 47%, 22% og 8% for dimensjonene ø8, ø16 og ø25 mm.

De rustfrie dimensjonene ϕ 10 og ϕ 12 mm tilfredsstilte derimot ikke kravene til kamgeometri og uttrekkskreftene var i dette tilfellet henholdsvis 7% og 13% lavere enn for vanlig armering. Det ble senere levert rustfri armering i disse dimensjonene som tilfredstilte kravene til ribbegeometri, men det ble ikke utført nye uttrekningsforsøk.

Glidningen ved brudd var større for rustfri armering enn for vanlig armering. Dette skyldes sannsynligvis redusert heftfasthet mellom betong og rustfritt stål enn for karbonstål.

STIKKORD	NORSK	ENGLISH
	Betong	Concrete
	Rustfri armering	Stainless steel reinforcement
	Kamgeometri	Rib geometry
	Heftfasthet	Bond strength

Rapport **Nr. 18** Heftforhold for rustfritt armeringsstål.

Prosjekt **Betongkonstruksjoners livsløp**
Et utviklingsprosjekt i samarbeid mellom offentlige
byggherrer, industri og forskningsinstitutter.

Aktivitet **DP2 C2** Vedlikeholds- og oppgraderingsmetoder
Rustfri armering
Heftforhold for rustfritt armeringsstål

Deltagere Statens vegvesen (prosjektledelse),
Forsvarsbygg,
NORCEM A.S,
Selmer Skanska AS,
Sika Norge AS,
Norges byggforskningsinstitutt,
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Emneord Betong
Rustfri armering
Kamgeometri
Heftfasthet

Key words Concrete
Stainless steel reinforcement
Rib geometry
Bond strength

FORORD

Fokus er i løpet av de senere årene flyttet fra bygging av nye konstruksjoner over mot forvaltning hvor det legges større vekt på problemstillinger knyttet til drift, vedlikehold og gjenbruk av eksisterende konstruksjoner.

Prosjektet “Betongkonstruksjoners livsløp” er knyttet opp mot denne typen utfordringer som en samlet bygg- og anleggsbransje står overfor. Kravene til bygg- og anleggskonstruksjoner er at de skal være funksjonelle og kostnadseffektive. Offentlige byggherrer forvalter og vedlikeholder et stort antall konstruksjoner som skal møte samfunnets krav til:

- sikkerhet
- kvalitet/økonomi
- miljø

Det ble de siste årene av 90-tallet lagt ned et betydelig arbeid i prosjektet “Bestandige betong-konstruksjoner”. Av resultatene fra dette prosjektet og erfaringene fra prosjektet ”OFU Gimsøystraumen” fremgår det klart at beslutningen om å bygge bestandige betongkonstruksjoner må tas tidlig i planleggingsfasen og at det er behov for enkelt å kunne verifisere prosjekteringsforutsetningene.

”Betongkonstruksjoners livsløp” bygger videre på forannevnte prosjekter. Hovedvekten er lagt på klart formulerte forskningsoppgaver som dels konkretiserer eksisterende kunnskap og dels fyller hull i kunnskapsgrunnlaget. Aktivitetene er valgt innenfor en ramme som omfatter alle faser fra planlegging til riving og gjenbruk.

Prosjektets hovedmålsetning har vært:

Kostnadseffektive og miljøgunstige betongkonstruksjoner

med følgende delmål:

- Identifisere hovedparametre i levetidsmodellene og kalibrere dem mot felterfaringer
- System for vurdering av vedlikeholdstiltaks levetid
- System for instrumentell overvåkning av betongkonstruksjoners tilstandsutvikling
- Kunnskapsformidling gjennom normarbeid, kurs og internasjonale nettverk

Prosjektets sluttprodukter er:

- Grunnlag for veiledninger og regler for levetidsprosjektering
- Akseptkriterier for bedømmelse av betongkonstruksjoners bestandighet
- Datagrunnlag til bruk i standardiseringsarbeid og som inngangsdata til europeisk nettverksarbeid
- Kunnskap og kompetanse knyttet til sensorteknologi, måleteknikk, “intelligent” instrumentell overvåkning, katodisk beskyttelse etc., hvor industripartnerne gis mulighet til å utnytte resultatene kommersielt

Prosjektet har bestått av flere større og mindre aktiviteter gruppert i følgende delprosjekter:

- DP1. Levetidsprosjektering
    - A. Datainnsamling
    - B. Levetidsmodeller
- DP2. Vedlikeholds- og oppgraderingsmetoder
    - A. Vedlikeholdsmetoder
    - B. Oppgraderingsmetoder
    - C. Rustfri armering
- DP3. Måleteknikk

Aktivitetene i prosjektet er basert på enkeltforslag fra prosjektdeltakerne. Hvor aktivitetene hadde fellestrekk, kunne levere resultater til, eller benytte resultater fra andre aktiviteter ble dette identifisert ved oppstarten av prosjektet og nødvendig koordinering foretatt. Ellers er aktivitetene styrt meget selvstendig.

Prosjektet startet høsten 1999 og ble avsluttet høsten 2001. Prosjektet har vært støttet av BA-programmet i Norges forskningsråd med NOK 1 mill i hvert av årene 1999 og 2000.

I tillegg til støtten fra Norges forskningsråd har det vært ytet en betydelig egeninnsats fra deltakerne i form av personalinnsats og kjøp av FoU-tjenester. Prosjektkostnadene per 31-12-00 var NOK 7,25 mill, hvorav NOK 2,7 mill var benyttet til kjøp av FoU-tjenester fra forskningsinstitutter og NOK 0,5 mill fra konsulent. I år 2001 ble det kjøpt tjenester for NOK 1,7 mill som i sin helhet ble finansiert av prosjektdeltagerne. Samlede prosjektkostnader ved avslutningen av prosjektet er ca. NOK 9 mill.

Prosjektet har hatt følgende deltakere:

Statens vegvesen
Forsvarsbygg
NORCEM A.S
Selmer Skanska AS
NTNU
SINTEF
Sika Norge AS
Norges byggforskningsinstitutt
NORUT Teknologi as

I tillegg har prosjektet samarbeidet med Det Norske Veritas og ARMINOX, som alle har bidratt med egeninnsats.

Det er knyttet to dr. gradsstudenter til prosjektet.
Prosjektet mottok i juni 2000 et 3 års dr.grad stipendium. Stipendiat ble tilsatt 01-01-2001.

Prosjektet har vært ledet av Vegdirektoratet. Prosjektledelsen, som har bestått av Finn Fluge Vegteknisk avdeling, Vegdirektoratet og Bernt Jakobsen, Aadnesen a.s, har rapportert til en styringskomite som har bestått av representanter fra prosjektdeltakerne. Styringskomiteen har vært samlet to ganger årlig eller ved behov og har fastlagt mål og hovedstrategier.

SUMMARY

A pullout test programme comparing bond properties of austenitic stainless steel reinforcement of two different types (ø 8, ø 10 and ø 12 mm cold drawn, W 1.4401, and ø 16 and ø 25 mm hot rolled, W 1.4429) with ordinary carbon reinforcement steel has been carried out.

Bond properties are specified in the Norwegian as well as the German codes through requirements to the rib geometry. Of these requirements the projected rib area is the main parameter determining the pullout resistance.

To enable a comparison of the pullout force of bars with the same diameter but of different materials and with different rib geometry the pullout forces for each type of bar have been normalised with respect to their projected rib areas.

All carbon steel bars and all ø 8, ø 16 and ø 25 mm stainless steel bars had rib geometry that complied with the code requirements.

The ø10 and ø12mm stainless steel bars had rib heights and projected rib areas, that did not comply with the code requirements.

The normalised pullout forces of the compliant stainless steel bars exceeded the normalised pullout forces of the corresponding carbon steel bars. This could indicate favourable detailed rib geometry compared to the rib geometry of the carbon steel bars. The non-compliant stainless steel bars had lower normalised pullout forces than the corresponding carbon steel bars. The slip at failure was larger for the stainless steel bars than for the carbon steel bars, which is explained by the known lower adhesion properties between stainless steel and concrete compared to carbon steel and concrete.

A new set of ø 10 and ø 12 mm stainless steel bars are now produced on a new straightening machine and these have compliant rib geometry. Unfortunately these were supplied after the testing was completed.

RAPPORTOVERSIKT

Rapport nr.1:	TITTEL**:**	Feltdata for kloridinitiert armeringskorrosjon. Sammenstilling og kvalitetsvurdering av tilgjengelige data.
	Aktivitet:	DP1 A1
	Utgiver:	Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. Intern rapport nr. 2197.
	Forfattere:	Skjølsvold, O., Jacobsen, S., Lahus, O., Lindgård, J., Hynne, T.
	ISSN	1502-2331
	ISBN	82-91228-04-3
	Sider:	12+9+7 vedlegg + CD-ROM
	Dato:	Desember 2002

Rapport nr. 2:	TITTEL:	Laboratoriedata for kloridinitiert armeringskorrosjon.
	Aktivitet:	DP1 A1
	Utgiver:	Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. SINTEF. Rapport nr. STF22 A00732.
	Forfattere:	Hynne, T. og Lindgård, J.
	ISSN	1502-2331
	ISBN	82-91228-07-8
	Sider:	13+35+16 vedlegg
	Dato:	Januar 2003

Rapport nr. 3:	TITTEL:	Gimsøystraumen bru. Spesialinspeksjon 1992-kloridprofiler. Vurdering av kloridbelastning og diffusjonskoeffisient
	Aktivitet:	DP1 A1
	Utgiver:	Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. Intern rapport nr. 2196.
	Forfattere:	Skjølsvold, O.
	ISSN	1502-2331
	ISBN	82-91228-08-6
	Sider:	14+18+3 vedlegg+CD-ROM
	Dato:	Januar 2003

Rapport nr. 4:	TITTEL:	Kloridinntrengning i ressursvennlig kvalitetsbetong.
	Aktivitet:	DP1 A2
	Utgiver:	Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. NORCEM rapport
	Forfattere:	Kjellsen, K.O. og Skjølsvold, O.
	ISSN	1502-2331
	ISBN	82-91228-09-4
	Sider:	14+16+13 vedlegg
	Dato:	Januar 2003

Rapport nr. 5: TITTEL: Statistisk beregning av levetid for betongkonstruksjoner utsatt for kloridinntrengning.
Aktivitet: DP1 B1
Utgiver: Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. SINTEF. Rapport nr. STF22 A01613.
Forfattere: Hynne, T., Leira, B.J., Carlsen, J.E. og Lahus, O.
ISSN 1502-2331
ISBN 82-91228-10-8
Sider: 14+59+3 vedlegg
Dato: Februar 2003

Rapport nr. 6: TITTEL: Dimensjoneringsformat for kloridbestandighet.
Aktivitet: DP1 B1
Utgiver: Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. SINTEF. Rapport STF22 A02601.
Forfattere: Leira, B.J.
ISSN 1502-2331
ISBN 82-91228-11-6
Sider: 14+36+ 1 vedlegg
Dato: Februar 2003

Rapport nr. 7: TITTEL: Pålitelighetsmetodikk ved bruk av FDV og levetidsberegninger.
Aktivitet: DP1 B2
Utgiver: Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. Aas-Jakobsen. Rapp 6943-01.
Forfattere: Larsen, R.M.
ISSN 1502-2331
ISBN 82-91228-12-4
Sider: 14 + 67
Dato: Februar 2003

Rapport nr. 8: TITTEL: Effekt av reparasjon på levetid: Eksempelstudie fra Gimsøystraumen.
Aktivitet: DP1 B3
Utgiver: Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. SINTEF. Rapport nr. STF22 A01607.
Forfattere: Hynne, T. og Leira, B.J.
ISSN 1502-2331
ISBN 82-91228-13-2
Sider: 12 + 22 + 7 vedlegg
Dato: Oktober 2006

Rapport nr. 9: TITTEL: Bestandighet og levetid av reparerte betongkonstruksjoner.
Aktivitet: DP2 A2
Utgiver: Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling.
NORUT Teknologi as rapport NTAS F2001-36.
Forfattere: Arntsen, B.
ISSN 1502-2331
ISBN 82-91228-14-0
Sider: 14 + 20
Dato: Oktober 2006

Rapport nr. 10: TITTEL: Restlevetid – Kai Sjursøya.
Aktivitet: DP2 A3
Utgiver: Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling.
Selmer Skanska AS, rapport nr. B 01-01.
Forfattere: Carlsen, J.E.
ISSN 1502-2331
ISBN 82-91228-15-9
Sider: 12 + 15 + 7 vedlegg
Dato: November 2006

Rapport nr. 11: TITTEL: Feltforsøk Sykkylven bru.
Aktivitet: DP2 A4
Utgiver: Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling.
Selmer Skanska AS, rapport nr. B 01-02
Forfattere: Carlsen, J.E.
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Sider: 12 + 9 +30
Dato: Desember 2006

Rapport nr. 12: TITTEL: Strengthening Prestressed Concrete Beams with Carbon Fiber Polymer Plates.
Aktivitet: DP2 B1
Utgiver: Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling.
NTNU, Institutt for konstruksjonsteknikk.
Forfattere: Takacs, P.F. og Kanstad, T.
ISSN 1502-2331
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Dato: Desember 2006

Rapport nr. 13: TITTEL: Forsterking av betongsøyler med karbonfibervev.
Aktivitet: DP2 B2
Utgiver: Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. SINTEF. Rapport nr. STF22 A00718.
Forfattere: Thorenfeldt, E.
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Sider: 14 + 22 + 3 vedlegg
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Rapport nr. 14: TITTEL: Forankringskapasitet av CFAP-bånd limt til betong.
Aktivitet: DP2 B2
Utgiver: Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. SINTEF. Rapport nr. STF22 A01618.
Forfattere: Thorenfeldt, E.
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Dato: November 2007

Rapport nr. 15: TITTEL: Nonlinear Finite Element Analysis of Deteriorated and Repaired RC Beams
Aktivitet: DP2 B3
Utgiver: Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. NORUT Teknologi as rapport NTAS F2001-31.
Forfattere: Sand, B.
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Rapport nr. 16: TITTEL: Styrkeberegning ved korrosjonsskader.
Aktivitet: DP2 B3
Utgiver: Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. SINTEF. Rapport nr. STF22 A01619.
Forfattere: Stemland, H.
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Rapport nr. 17:	TITTEL:	Korrosjonsegenskaper for rustfri armering.
	Aktivitet:	DP2 C1
	Utgiver:	Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. NTNU, Institutt for konstruksjonsteknikk. Rapport R-9-01.
	Forfattere:	Vennesland, Ø.
	ISSN	1502-2331
	ISBN	82-91228-22-1
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	Dato:	Januar 2008
Rapport nr. 18:	TITTEL:	Heftforhold for rustfritt armeringsstål.
	Aktivitet:	DP2 C2
	Utgiver:	Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling. NTNU rapport.
	Forfattere:	Hofsøy, A., Sørensen, S.I. og Markeset, G.
	ISSN	1502-2331
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Rapport nr. 19:	TITTEL:	Service Life Design of Concrete Structures
	Aktivitet:	DP1 B4
	Utgiver:	Statens vegvesen, Vegdirektoratet, Vegteknisk avdeling.
	Forfattere:	Helland, S., Maage, M., Smeplass, S., Fluge, F.
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Rapport nr. 20:	TITTEL:	SLUTTRAPPORT
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INNHOLDSFORTEGNELSE

NTNU rapport, 2001
Hofsøy, A., Sørensen, S.I., Markeset, G.
”Heftforhold for rustfritt armeringsstål”.

SAMMENDRAG

Kjennskap til armeringens heftegenskaper er en viktig parameter når bruk av rustfri armering i betongkonstruksjoner vurderes. Kravene til heftegenskaper er i norske og tyske regler kun uttrykt ved et minimumskrav til den såkalte projiserte kamfaktoren.

På denne bakgrunn er det utført laboratorieforsøk for bestemmelse av heftegenskapene til to typer austenittisk, rustfritt armeringsstål. Målsettingen var å sammenligne heftegenskapene i betong for de aktuelle rustfrie armeringstypene med tilsvarende egenskaper for armering fremstilt av vanlig karbonstål samt sammenligne kamgeometrien med krav i regelverket.

Forsøksprogrammet omfattet måling av heftegenskaper ved uttrekksforsøk, kontroll av betongens trykkfasthet og måling av armeringens kamgeometri

Den rustfrie armeringen var kaldtrukket stål, W 1.4401, med dimensjon ϕ 8, ϕ 10 og ϕ 12 mm og varmvalset stål, W 1.4429, med dimensjon ϕ 16 og ϕ 25 mm.

Alle prøvene av karbonstål og de rustfrie ϕ 8, ϕ 16 og ϕ 25 mm stengene hadde kamgeometri i overensstemmelse med kravene i regelverket. De rustfrie ϕ 10 og ϕ 12 mm stengene tilfredsstilte derimot ikke kravene.

For å kunne sammenligne heftegenskapene til armering med samme diameter, men med forskjellig kamgeometri ble resultatene normalisert basert på projisert kamareal.

De normaliserte uttrekkskreftene for de rustfrie armeringsstengene som tilfredsstilte kravene til kamgeometri var høyere enn for de tilsvarende for sammenlignbare armeringsstenger av karbonstål. For dimensjonene ϕ 8, ϕ 16 og ϕ 25 mm var forskjellen henholdsvis 47%, 22% og 8%. Dette kan indikere at disse stengene hadde gunstigere ribbeutforming enn de øvrige.

For de rustfrie armeringsstengene som ikke tilfredsstilte kravene til kamgeometri var forholdet motsatt. De normaliserte uttrekkskreftene var i dette tilfellet lavere enn for tilsvarende armering av karbonstål. For dimensjonene ϕ 10 og ϕ 12 mm var forskjellen henholdsvis 7% og 13%. Det ble opplyst fra armeringsprodusenten at de stengene som ikke oppfylte kravene til kamgeometri var blitt fremstilt med gammelt produksjonsutstyr. Det ble senere levert armeringsstål med disse diametre som tilfredsstilte kravene. Det ble imidlertid ikke utført uttrekksforsøk med disse.

Glidningen ved brudd var større for rustfri armering enn for vanlig armering. Dette skyldes sannsynligvis redusert heftfasthet mellom betong og rustfritt stål enn mellom betong og karbonstål.

BETONGKONSTRUKSJONERS LIVSLØP

DP2 C2 Heftforhold for rustfritt armeringsstål

Audun Hofsøy, NTNU

Svein Ivar Sørensen, NTNU

Gro Markeset, FBT

NOTATIONS

B = Carbon steel

W = Austenitic stainless steel

B 500 C - steel : Carbon steel according to NS 3576-3

W 1.4401-steel : Cold drawn stainless steel

W 1.4429-steel : Hot rolled stainless steel

R_e = yield strength of steel

$R_{p0.2}$ = 0.2 % proof stress of steel

R_m = Tensile strength of steel

A_{gt} = strain at maximum stress for steel

E_s = Modulus of elasticity of steel

f_c = Compressive concrete cube strength

f_R = Projected rib factor

$f_{R,\,req}$ = Required projected rib factor

$f_{R,\,meas}$ = Measured projected rib factor

f_{bu} = Ultimate bond stress-Bond strength

$\frac{f_{bu\ W\ 1.4401}}{f_{bu\ B\ 500\ C}}$ = Bond strength ratio

$\frac{f_{bu\ W\ 1.4429}}{f_{bu\ B\ 500\ C}}$ = Bond strength ratio

$\frac{f_{b\ W\ 1.4401}}{f_{b\ B\ 500\ C}}$ = Bond stress ratio

$$\frac{f_{b\ W\ 1.4429}}{f_{b\ B\ 500\ C}} = \text{Bond stress ratio}$$

$$f_{bu,\ norm} = f_{bu,\ meas}\left(\frac{f_{R,req}}{f_{R,meas}}\right) = \text{Normalised bond strength}$$

1 INTRODUCTION

1.1 Background

Corrosion of steel reinforcement in concrete is one of the major problems with respect to the durability of reinforced concrete structures. In most cases the corrosion is caused by carbonation of the concrete or by high chloride content in the concrete.

Many corrosion protection methods have been developed and tested, however very few of these methods are found to provide good protection.

Some of the types of stainless steel reinforcement show excellent corrosion resistance. These types of reinforcement may eliminate reinforcement corrosion providing more durable concrete structures even under very aggressive conditions.

In order to evaluate the applicability of stainless steel reinforcement in concrete structures the bond property is an essential parameter. According to Norwegian and German codes the requirements to bond is expressed as the minimum value of the projected rib factor only.

On request from Norwegian Defence Construction Service, FBT, Oslo and ARMINOX, Denmark, an experimental test of the bond properties of two types of austenitic stainless steel reinforcement has been carried out.

1.2 Aim

The aim of the experimental test was to investigate the bond properties in concrete of the actual types of stainless steel reinforcement and compare the results with the bond properties of ordinary carbon steel reinforcement and check the rib geometry with respect to the code requirements.

2 TEST PROGRAMME

2.1 General

The experimental work includes

- testing of bond properties by a pullout test method
- control test of compressive strength of the concrete
- measuring of the rib geometry of the reinforcement steel

2.2 Test methods

The following test methods were used

- Bond properties
  With some modifications as to the concrete:
  RILEM/CEN/FIP RECOMMENDATIONS ON REINFORCEMENT
  STEEL FOR REINFORCED CONCRETE

  RC 6 Bond Test for Reinforcement Steel: 2. Pull-out Test (Revised Edition, may 1983), [1].
  In fig 1 the testing set-up is shown.

- Compressive strength of concrete
  Norwegian Code NS 3668 Concrete testing. Hardened concrete. Compressive strength, 1987

- Rib geometry
  Norwegian Code NS 3576 -3 Steels for reinforcement of concrete. Dimensions and properties. Part 3: Ribbed bars B 500 C, [2].

2.3 Specimens

The dimensions of the pullout specimens and the length of the embodiment of the reinforcing bars are shown in fig 2.

The specimens for control of the compressive strength of the concrete were 100x100x100 mm cubes.

2.4 Material properties

2.4.1 Concrete

The mix proportion of the concrete, relative to the cement content, was:

Water	0.52
Cement (NORCEM)	1.00
Sand, 0-8 mm	2.94
Coarse aggregate: 8-11 mm	1.03
11-16 mm	1.19
Sikament 92	0.004

2.4.2 Reinforcement

The carbon steel, B 500 C, was produced by Fundia, Mo, Norway and was ordinary ribbed bars according to the Norwegian code NS 3576-3. This type of reinforcing steel is the one that is mostly used for reinforced concrete structures in Norway. The chemical composition of the B 500 C steel is given in Table 1 and the required mechanical properties in Table 2.

The stainless steel reinforcement used in the test was provided by ARMINOX, Denmark. In agreement with FBT and ARMINOX the following grades of stainless ribbed bars were chosen for testing:

W 1.4401, which is a cold drawn austenitic steel. Nominal diameter: 8,10 and 12 mm.

W 1.4429, which is a hot rolled austenitic steel. Nominal diameter: 16 and 25 mm.

The chemical composition of the W 1.4401 and the W 1.4429 steel is given in Table 1 and the mechanical properties in Table 2.

Photos of the actual types of reinforcement steel are shown in fig 4.

2.5 Test programme

In Table 3 the programme for the pullout test is shown. As can be seen from Table 3, the test includes six presumptively identical specimens of each type.

In addition to the pullout specimens three control specimens, 100x100x100 mm cubes, should be cast from each concrete batch.

3 FABRICATION AND TESTING

3.1 Casting and curing

The concrete had a slump that ranged from 90 to 180 mm, and the air content ranged from 0.8 to 2.2 %.

The pullout specimens were cast with the reinforcing bar in a horizontal position, see fig 2. Form removal was carried out two days after casting. During the time from casting to testing, at 28 days, all specimens were moist cured at + 20°C.

3.2 Testing procedures

The pullout testing was carried out in a hydraulic testing machine with a maximum load capacity of 500 kN. In fig 3 the testing rig is shown. The load was applied continuously. The slip was measured at the unloaded end of the bar and was recorded together with the simultaneous load.

The control specimens were tested in a hydraulic testing machine of 3000 kN load capacity.

4 RESULTS AND DISCUSSION

4.1 Concrete strength

Due to special reasons the testing was carried out during several months. The rather long time between some of the tests involved use of different aggregates for the concrete. It is thought that this is the reason why the concrete strength varied as can be seen in Table 4. In the cases where there is a difference between the concrete strength for specimens with B 500 C and W 1.4401 the pullout results are adjusted based on the mean concrete strength. This adjustment applies to the results for 10 and 12 mm bars.

4.2 Rib geometry

In order to evaluate the applicability of stainless steel reinforcement in concrete structures the bond property is an essential parameter. According to Norwegian and German codes the requirements to bond is mainly expressed as the minimum value of the projected rib factor. Therefore, it has been necessary to measure the rib geometry of the actual bars. The measurements, were carried out in accordance with the rules in the Norwegian code, NS 3576-3, 1997 [2], which are very much like the rules given in the German code DIN 488, 1986 [3], see fig. 5. The results of the measurement of the rib geometry are shown in Table 5.

All the B 500 C-bars had the same type of rib pattern: two longitudinal ribs, transverse ribs with one rib angle on one side (marked A in Table 5) and transverse ribs with two different rib angles on the other side (marked B1 and B2 in Table 5).

The W 1.4401-bars had all the same type of rib pattern: none longitudinal ribs, three rows of transverse ribs with the same rib angle in each row (marked A, B and C in Table 5).

The W 1.4429-bars had all the same type of rib pattern: two longitudinal ribs, transverse ribs on the two sides and the same rib angle on both sides (marked A and B in Table 5).

In addition to the measured value of the rib geometry the code requirements are listed in Table 5. The required values for B 500 C are taken from NS 3576-3 and for W 1.4401 and W 1.4429 from DIN 488.

The rib angle and the rib spacing seem to be within the required range for all the bars.

The rib height for B 500 C-steel is well above the required height for all the actual dimensions. That is, however, not the case for the W 1.4401-steel, that has a lower rib height than required for all the actual dimensions except at the center of the ribs of 8 mm bars. For dimension 8 mm the difference between required and measured rib height is rather small, however, for dimension 10 and especially for 12 mm the rib height is very much lower than required.

The rib heights of the 16 and 25 mm W 1.4429-bars met the code requirements.

The most important criterion for acceptance of the rib geometry is the projected rib factor, f_R.

For all the 8 mm bars the measured projected rib factors, f_R , meet the code requirements. The f_R - values for the W 1.4401-steel bar and the B 500 C-steel bar are 13% and 53% higher than required, respectively.

The 10 and 12 mm B 500 C bars have projected rib factors being 33% and 14% higher than required, respectively, while the W 1.4401-bars of the corresponding diameters has a low projected rib factors that do not meet the requirements. The projected rib factor for the 10 mm and the 12 mm W 1.4401-steel bars is 13% and 34 % lower than the required value.

Projected rib factors for the B 500 C-steel of 16 and 25 mm diameter have rather high values, 41% and 36% above required value, respectively. The hot rolled W 1.4429-steel bars of 16 and 25 mm diameter meet the requirement, as their f_R-values were 5% and 11% higher than required, respectively.

4.3 Bond strength

Observed bond strengths of the pullout tests are shown in Table 6.

For the present comparisons the bond strengths of deformed bars may be assumed to be approximately proportional to the projected rib area, f_R, when considering the range of variations in f_R observed in these tests.

Comparing the bond strength of stainless steel bars and carbon steel bars of equal diameters, but with differences in f_R, therefore requires a correction of the measured bond strength with respect to the relative projected rib areas.

In Table 7 the ratio between the measured bond strengths of the stainless steel bars and the carbon steel bars has been corrected with the ratio between the f_R value of the carbon steel bars and the stainless steel bars. This allows the bond strengths of the ø10 mm and ø12 mm stainless steel bars to be compared relatively to the bond strength of the similar carbon steel bars. This in spite of the fact that the stainless steel bars of these two diameters did not comply with the code requirements with respect to $f_{R,}$, and thus also had a low bond strength in the tests.

The normalised bond strength of steinless steel relative to carbon steel is further illustrated in fig 6. This figure clearly illustrates that the tested stainless steel reinforcement of diameter 8, 16, 25 has a higher bond strength than the carbon steel when normalised to the rib factor requirement. Further, the very low bond strength observed for W 1.4401-steel of 10 and 12 mm diameter with the low f_R, appears clearly from fig 6.

The reason why the bond strength of the W 1.4401-steel of 8 mm diameter seems to be somewhat higher than that of the corresponding B 500 C-steel cannot be due to the level of the projected rib factor. What causes the higher bond strength in this case is not clarified.

4.4 Stress-slip relation

In fig 7 to 16 stress-slip curves from the pullout testing are shown. The curves include the recorded slip at the unloaded end of the bar up to a value of 5 mm. The bond stress is calculated as a uniform stress on the embedded length of the bar using the nominal diameter of the bar. As mentioned earlier an adjustment of the bond stress is carried out for different compressive strength of the concrete for the B 500 C- and the W 1.4401-specimens with 10 and 12 mm bars. It can be seen from the strength values in Table 4, that the concrete strength is different for different bar diameters. This means that the stress-slip curves can only be directly compared for each bar diameter.

The stress-slip curves for the bars of 8 mm diameter show the same tendency as found from Table 6: The deviation is higher for B 500 C-steel than for W 1.4401-steel, se fig 7 and 8.

For the bars of 10 and 12 mm diameter the stress-slip curves are very much the same: lower bond strength and lower deviation for the W 1.4401-steel, see fig 9, 10, 11 and 12.

In fig 13 and 14 the stress-slip curves for the bars of 16 mm diameter show rather small deviation, however, the curves for W 1.4429-steel have a somewhat divergent course with a higher slip at ultimate bond strength.

Typical for the stress-slip curves for the 25 mm bars, see fig 15 and 16, are that the course after maximum stress are declining very little. That means that the bond stress at 5 mm slip is rather high. The deviation is at a medium level, somewhat higher for the B 500 C-steel than for the W 1.4420-steel.

To examine the slip course more in detail some results from the stress-slip curves are presented in Table 8. This table gives the nominal bond stress for different slip values. The bond stress ratio f_b W 1.44xx/f_b B 500 C is used to evaluate the stress-slip properties of the different bars.

The 8 mm W 1.4401-steel reaches a higher bond stress at 0.01 and 0.05 mm slip than the corresponding B 500 C-steel; the stress ratio is higher than 1.0. At higher slip values the bond stress is almost the same for the two steel qualities. This means that the slip properties of the 8 mm W 1.4401-steel are very good.

When it comes to the 10 and 12 mm bars, the situation is quite different. The bond stress ratio for the 10 mm bars is about 0.50 for all the actual slip values. For the 12 mm bars the bond stress ratio is even somewhat lower. These values of the bond stress ratio show that the slip of the W 1.4401-steel starts at a very low bond stress compared to the B 500 C-steel. At higher values of slip the same tendency can be seen: the bond stress at any level in Table 8 is much lower for the W 1.4401-steel. The slip properties of the 10 and 12 mm W 1.4401-steel are poor, and must be considered as not acceptable due to the low projected rib factor for these two diameter bars, see Section 4.2.

The 16 mm W 1.4429-steel shows a good performance as to the bond stress ratio at different slip levels. The bond ratio varies from 1.15 to 0.89 with increasing slip values.

The W 1.4429-steel of 25 mm diameter shows bond stress ratios that increase from 0.74 to 0.85 with increasing slip values. This means that the slip properties of the 25 mm W 1.4429-steel are not quite as good as that of the B 500 C-steel, but are acceptable.

In Table 6 the observed bond strength is approximately normalised by dividing the bond strength values by the compressive cube strength: f_{bu} / f_c. In this way the results of all diameters and steel types specifically provided for these tests, can be compared.

Fig 17 shows the f_{bu} / (f_c x $f_{R,meas}$) ratio for the actual bar diameters and steel types.

Slip at maximum bond stress, or bond strength, for the actual bars is given in fig 18. For the B 500 C-steel the slip values increase with the diameter of the bar, except for 16 mm diameter. However, the two stainless steel designations give a somewhat higher slip at maximum bond stress for all bar dimensions.

4.5 New delivery of W 1.4401 ø 10 and ø 12 mm

The testing of the rib geometry of the stainless bars with ø10 mm and ø12 mm has shown that the rib geometry and the projected rib areas do not comply with the corresponding code requirements. The investigation at ARMINOX of the cause of this discrepancy has shown that these samples were erroneously supplied without the usual quality control procedures, and were due to a misalignment of an older straightening machine used to straighten these diameter bars from coils. This machine has since been replaced, and a new set of samples produced on the new machinery has been forwarded for renewed testing.

The measurements of rib geometry and projected rib areas of these new samples of ø 10 mm and ø 12 mm of W 1.4401, complied with the specified code requirements, as seen from Table 9 and 10.

5 CONCLUSIONS

The bond properties of two designations of stainless steel reinforcement ribbed bars have been compared with ordinary carbon steel ribbed bars. Due to differences in rib geometry the values of the pullout tests have been normalised with respect to the minimum required projected rib area. The following conclusions can be drawn from these tests:

- all B 500 C-steel bars had rib geometry which, met all code requirements with a large margin.
- the ø 8 mm W 1.4401-steel bars and the ø 16 mm and ø 25 mm W 1.4429-steel bars had rib geometry, which met al code requirements with a small margin.
- the ø 10 mm and ø 12 mm W 1.4401-steel bars had rib heights and projected rib areas, which were considerably below the code requirements and were thus non-compliant.
- a comparison has been made between the pullout force of stainless steel bars and the corresponding carbon steel bars by normalising the forces with respect to the projected rib factors. The following comparative results were found:

  - the ø 8 mm, ø 16 mm and ø 25 mm stainless steel bars exceeded the normalised pullout force of the corresponding carbon steel bars by 47%, 22% and 8% respectively.
  - the ø 10 mm and ø 12 mm stainless steel bars had normalise pullout forces being 7% and 13% below the corresponding values of the corresponding steel bars.

– the slip at failure of the stainless steel bars were throughout larger than the slip of the carbon steel bars. This is to be expected due to the known lower adhesion between stainless steel and concrete compared to the adhesion between carbon steel and concrete.

– the tests have shown that the ø 10 mm and ø 12 mm stainless steel bars provided for these tests were non-compliant with respect to rib geometry and that the normalised bond strengths were also below the values for the corresponding carbon steel bars. According to ARMINOX the ø 10 mm and ø 12 mm stainless steel bars provided for these tests were produced on an older straightening machine having erroneously been misaligned. This machine has now been replaced with a new machine. New samples produced on the new machine have now been provided. Measurements of the rib geometry of these new samples have shown compliance with the code requirements.

– the normalised pullout strengths of the three diameter compliant stainless steel bars, which are above the normalised pullout strengths of the corresponding carbon steel bars seem to indicate a somewhat superior detailed rib geometry of the stainless steel bars. The same rib geometry would be expected to provide a slightly higher relative pullout force for the carbon steel than for the stainless steel bars due to the superior adhesion of the carbon steel, which is the opposite of what was found in the tests.

6 REFERENCES

[1] RILEM/CEN/FIP RECOMMENDATIONS ON REINFORCEMENT STEEL FOR REINFORCED CONCRETE
RC6 Bond test for reinforcement steel: Pull-out test (Revised edition, May 1983)

[2] NS 3576-3 Steels for reinforcement of concrete. Dimensions and properties.
Part 3: Ribbed bars B 500 C, Oslo 1997

[3] DIN 488 Betonstahl, 1984/-86

7 FIGURES AND TABLES

Table 1

Table 1: Chemical composition of steel

Steel code	Carbon C	Silicon Si %	Manganese Mn %	Phosphorus P %	Sulphur S %	Chrome Cr %	Molybdenum Mo %	Nickel Ni %	Nitrogen N %
Carbon steel									
B500 C[1]	≤ 0.22	≤ 0.60	≤ 1.60	≤ 0.05	≤ 0.05				≤ 0.012
NS 3576-3,1997[2] ENV 10080,1995									
Stainless steel (Austenitic)[3]									
W 1.4401 (Cold drawn)	≤ 0.07	≤ 1.00	≤ 2.00	≤ 0.045	≤ 0.030	16.5 - 18.5	2.00 - 2.50	10.5 - 13.5	
W 1.4429 (Hot rolled)	≤ 0.03	≤ 1.00	≤ 2.00	≤ 0.045	≤ 0.025	16.5 - 18.5	2.50 - 3.00	11.5 - 14.5	0.14 - 0.22
Eurocode									

[1] Carbon eqvivalent $C_E = C + Mn/6 + (Cr + V + Mo)/5 + (Cu + Ni)/15 \leq 0.50$

[2] NS : Norwegian Code

[3] Data from ARMINOX

Table 2

Table 2 : Mechanical properties of steel

Steel code	Nominal diameter φ mm	Yield strength R_e N/mm^2	0.2 % proof stress $R_{p0.2}$ N/mm^2	Tensile strength R_m N/mm^2	R_m/R_e	$R_m/R_{p0.2}$	A_{gt} %	A_J/A10 %	Modulus of elasticity E_s kN/mm^2	Thermal expansion coefficient 10^{-6}/°C
Carbon steel B 500 C NS 3576-3,1997[1] ENV 10080, 1995	6 - 40	500		575	1.15		8.0		200	10.0 - 12.0
Stainless steel (Austenitic) [2]										
W 1.4401 (Cold drawn)	3 - 16		550	600		1.09		≥ 3/15	200	16.0
W 1.4429 (Hot rolled)	16 - 30(40)		550	700		1.27		≥ 3/15	200	16.0
Eurocode										

[1] NS : Norwegian Code

[2] Data from ARMINOX

Table 3

Table 3: Test programme: Pullout test

Nominal bar diameter mm	Number of pullout specimens			
	Carbon steel B 500 C	Stainless steel W 1.4401 (Cold drawn)	Stainless steel W 1.4429 (Hot rolled)	Total
8	6	6		12
10	6	6		12
12	6	6		12
16	6		6	12
25	6		6	12
Total	30	18	12	60

Table 4

Table 4: Concrete strength

Pullout specimen		Cube strength f_c N/mm^2
Nominal bar diameter mm	Steel type	
8	B 500 C W 1.4401	51.5
10	B 500 C W 1.4401	62.2 57.0
12	B 500 C W 1.4401	54.6 57.0
16	B 500 C W 1.4429	58.9
25	B 500 C W 1.4429	54.7

Table 5

Table 5 : Rib geometry

Steel type	Nominal diameter φ mm	Side	Rib angle, β		Rib height, h_1		Rib spacing, s		Projected rib factor f_R	
			Measured °	Required °	Measured mm	Required mm	Measured mm	Required mm	Measured	Required min
B 500 C	8	A B1 B2	64,0 62.0 46.0	35-75	0.698 0.825 0.756	0.40 min	5.98 10.38 10.38	4.0-8.0	0.069	0.048
W 1.4401	8	A B C	53.0 54.0 54.0	40-60 45-70	0.448 0.598 0.459	0.52-0.55	5.58 5.38 5.74	5.7-6.0	0.051	0.045
B 500 C	10	A B1 B2	58.0 65.0 45.0	35-75	0.784 0.720 0.650	0.50 min	6.47 13.08 13.08	5.0-8.0	0.069	0.052
W 1.4401	10	A B C	54.0 52.0 54.0	40-60 45-70	0.441 0.526 0.461	0.65-0.75	6.53 6.49 6.64	6.5-7.0	0.045	0.052
B 500 C	12	A B1 B2	56.0 65.0 45.0	35-75	0.954 0.802 0.934	0.60 min	7.98 15.80 15.80	6.0-9.6	0.064	0.056
W 1.4401	12	A B C	53.0 53.0 56.0	40-60 45-70	0.532 0.498 0.764	0.78-0.97	7.72 7.72 7.60	7.2-8.4	0.037	0.056
B 500 C	16	A B1 B2	58.0 70.0 49.0	35-75	1.052 1.079 0.995	0.80 min	9.33 18.70 19.05	8.0-12.5	0.079	0.056
W 1.4429	16	A B	58.0 56.0	45-50 65-70	1.226 1.302	1.04	9.43 9.47	9.6	0.059	0.056
B 500 C	25	A B1 B2	60.0 66.0 53.0	35-75	1.655 1.705 1.434	1.20 min	14.18 28.44 28.48	12.5-20.0	0.076	0.056
W 1.4429	25	A B	59.0 59.0	45-50 65-70	1.788 1.933	1.82	14.33 14.22	15.0	0.062	0.056

Table 6: Bond strength and slip at max load

Pullout specimen		Carbon steel B 500 C (NS 3576-3)			Stainless steel W 1.4401 (Cold drawn)			Stainless steel W 1.4429 (Hot rolled)		
Nominal bar diameter mm	No	Bond strength f_{bu} N/mm^2	Slip at max load mm	$\frac{f_{bu}}{f_c}$	Bond strength f_{bu} N/mm^2	Slip at max load mm	$\frac{f_{bu}}{f_c}$	Bond strength f_{bu} N/mm^2	Slip at max load mm	$\frac{f_{bu}}{f_c}$
8	1	21.44	1.2	0.416	23.80	1.2	0.462			
	2	24.16	1.0	0.469	20.90	1.3	0.406			
	3	17.73	0.9	0.344	20.22	1.0	0.393			
	4	22.04	0.9	0.428	24.90	1.0	0.483			
	5	22.65	1.0	0.440	23.26	1.2	0.452			
	6	17.71	-	0.344	23.45	1.2	0.455			
Mean		21.00	1.00	0.408	22.76	1.15	0.442			
Standard deviation		2.66			1.81					
10	1	17.25	1.3	0.289	9.31	1.7	0.156			
	2	23.65	1.1	0.397	10.51	1.8	0.176			
	3	19.09	1.0	0.320	12.01	1.2	0.202			
	4	16.51	1.4	0.277	9.42	1.5	0.158			
	5	19.35	1.3	0.325	9.75	1.8	0.164			
	6	20.97	0.9	0.352	9.80	1.5	0.164			
Mean		19.47	1.17	0.327	10.13	1.58	0.170			
Standard deviation		2.62			1.01					
12	1	23.35	1.4	0.418	11.52	1.4	0.206			
	2	23.51	1.3	0.421	8.93	1.5	0.160			
	3	18.02	1.2	0.323	12.19	1.6	0.218			
	4	22.13	1.6	0.397	10.03	1.4	0.180			
	5	18.40	1.4	0.330	11.36	1.7	0.204			
	6	18.11	1.5	0.325	11.01	1.6	0.197			
Mean		20.59	1.40	0.369	10.84	1.53	0.194			
Standard deviation		2.69			1.20					
16	1	19.50	1.4	0.331				16.00	1.3	0.272
	2	17.90	1.5	0.304				18.07	1.2	0.307
	3	18.85	1.3	0.320				17.90	1.7	0.304
	4	18.15	1.4	0.308				15.04	1.7	0.255
	5	17.53	1.3	0.298				17.36	1.7	0.295
	6	18.87	0.9	0.320				16.63	1.4	0.282
Mean		18.47	1.30	0.314				16.83	1.50	0.286
Standard deviation		0.73						1.17		
25	1	15.87	1.6	0.290				16.33	-	0.297
	2	17.16	1.8	0.314				13.63	-	0.249
	3	20.07	1.9	0.367				16.92	1.9	0.309
	4	17.49	1.5	0.320				17.42	2.7	0.318
	5	19.33	1.4	0.353				14.58	1.8	0.267
	6	16.58	2.2	0.303				15.10	2.4	0.276
Mean		17.75	1.73	0.324				15.66	2.2	0.286
Standard deviation		1.62						1.47		

Table 7

Table 7: Bond strength ratio and projected rib factor

Steel type **B and W**	**Nominal bar diameter**	**Bond strength measured**	**Projected rib factor** f_R		**Bond strength normalised to rib factor requirement**	**Normalised bond strength of W relative to B**
	mm	f_{bu} N/mm^2	Measured $f_{R,meas}$	Required $f_{R,req}$	$f_{bu,\,norm} = f_{bu,\,meas}\left(\frac{f_{R,req}}{f_{R,meas}}\right)$ N/mm^2	$\frac{f_{bu},W_{norm}}{f_{bu},B_{norm}} \bullet 100$ %
B 500 C W 1.4401	8	21.00 22.76	0.069 0.051	0.045 0.045	13,7 20,1	+46.7
B 500 C W 1.4401	10	19.47 10.13	0.074 0.045	0.052 0.052	13.7 11,7	-6,6 1)
B 500 C W 1.4401	12	20.59 10.84	0.064 0.037	0.056 0.056	18,0 16,4	-12.7 1)
B 500 C W 1.4429	16	18.47 16.83	0.079 0.059	0.056 0.056	13,1 16,0	+22.0
B 500 C W 1.4429	25	17.75 15.66	0.076 0.062	0.056 0.056	13,1 14,1	+8.1

1) Normalised bond strength has been corrected by the ratio of f_c from table 4. For Ø10 the factor is 1.099 and for Ø12 the factor is 0.958

Table 8a

Table 8a: Bond stress at different slip values

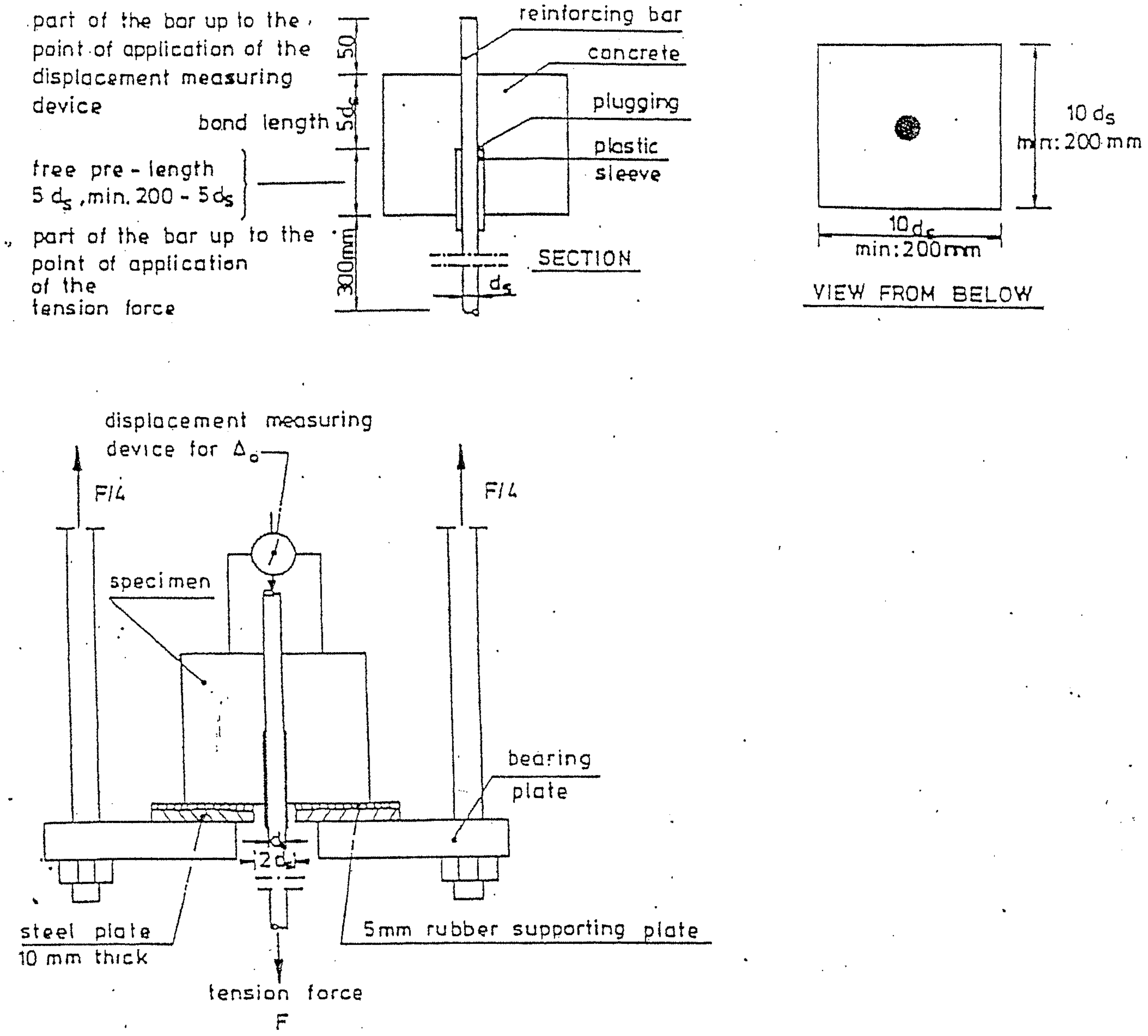
Pullout specimen		Nominal bond stress, f_b, N/mm^2, at different slip values														
Nominal bar diameter mm	No	0.01 mm			0.05 mm			0.10 mm			0.20 mm			0.50 mm		
		B 500 C	W 1.4401	W 1.4429	B 500 C	W 1.4401	W 1.4429	B 500 C	W 1.4401	W 1.4429	B 500 C	W 1.4401	W 1.4429	B 500 C	W 1.4401	W 1.4429
8	1	0,8	3.8		4.0	5.4		8.2	11.6		13.1	15.2		18.7	20.6	
	2	2.5	1.9		6.9	3.5		10.9	6.1		15.7	9.9		21.7	16.6	
	3	3.2	2.6		4.5	4.6		9.6	7.1		12.3	10.8		16.2	16.6	
	4	1.4	3.6		2.2	7.9		6.4	11.6		11.1	16.0		19.3	21.8	
	5	1.1	1.5		3.9	2.8		8.7	5.2		13.6	12.0		19.8	18.4	
	6	-	1.5		-	3.5		-	7.3		-	12.5		-	19.2	
Mean		1.86	2.48		4.30	4.62		8.76	8.15		13.16	12.73		19.14	18.87	
f_b W 1.44xx/f_b B 500 C			1.33			1.07			0.93			0.97			0.99	
10	1	1.9	1.2		4.0	2.1		5.7	3.2		8.3	4.8		14.3	6.9	
	2	2.1	0.7		4.4	1.5		7.1	2.2		9.4	4.0		20.2	7.4	
	3	2.3	1.3		4.9	2.6		7.1	3.7		10.0	5.5		16.6	10.1	
	4	1.1	1.3		2.7	2.4		4.4	3.4		8.0	4.6		14.2	6.9	
	5	2.7	1.1		5.2	2.0		8.0	2.9		11.4	3.8		16.3	6.3	
	6	2.5	1.1		5.5	2.2		8.8	2.9		13.6	4.5		19.0	7.6	
Mean		2.10	1.12		4.45	2.13		6.85	3.05		10.11	4.53		16.77	7.53	
f_b W 1.44xx/f_b B 500 C			0.53			0.48			0.45			0.45			0.45	
12	1	1.8	0.7		6.0	2.0		8.0	3.0		12.2	4.6		19.5	8.5	
	2	0.5	0.6		3.2	1.1		6.5	1.6		10.9	2.9		19.0	5.0	
	3	3.5	0.9		4.9	1.3		6.2	2.7		8.6	4.1		14.5	8.8	
	4	2.5	0.8		4.3	1.4		5.7	2.2		9.0	3.7		16.4	7.8	
	5	2.8	0.8		4.9	2.0		6.5	3.0		8.5	4.1		13.3	7.0	
	6	2.9	1.7		3.4	3.2		5.9	4.4		8.1	6.0		13.0	8.5	
Mean		2.33	0.92		4.45	1.83		6.47	2.82		9.55	4.23		15.95	7.60	
f_b W 1.44xx/f_b B 500 C			0.39			0.41			0.44			0.44			0.48	

Table 8a

Table 8a: Bond stress at different slip values

Pullout specimen		Nominal bond stress, f_b, N/mm^2, at different slip values														
Nominal bar diameter mm	No	0.01 mm			0.05 mm			0.10 mm			0.20 mm			0.50 mm		
		B 500 C	W 1.4401	W 1.4429	B 500 C	W 1.4401	W 1.4429	B 500 C	W 1.4401	W 1.4429	B 500 C	W 1.4401	W 1.4429	B 500 C	W 1.4401	W 1.4429
16	1	2.4		3.2	5.4		5.5	7.9		7.7	11.8		10.3	17.1		14.3
	2	1.9		3.0	4.1		5.0	6.2		7.2	9.0		10.4	14.9		14.9
	3	3.0		1.2	4.7		3.0	6.8		4.7	10.5		8.5	16.3		13.5
	4	1.5		1.5	3.0		3.2	4.2		5.0	6.6		7.9	14.5		12.9
	5	1.3		3.1	3.0		5.5	4.8		7.8	8.3		10.5	14.4		14.0
	6	2.1		2.0	4.5		3.5	6.9		5.1	11.0		8.0	16.8		13.8
Mean		2.3		2.33	4.12		4.30	6.13		6.25	9.53		9.27	15.67		13.90
f_b W 1.44xx/f_b B 500 C				1.15			1.04			1.02			0.97			0.89
25	1	2.5		1.9	4.5		3.7	5.9		5.1	8.3		7.5	12.4		12.6
	2	2.5		1.0	4.1		4.0	5.4		6.0	8.0		8.6	13.3		13.1
	3	2.5		1.5	4.4		2.7	6.3		3.5	9.5		5.5	15.5		10.0
	4	2.1		1.6	4.2		2.8	6.1		4.1	9.0		6.1	14.0		10.3
	5	2.5		-	4.9		-	7.0		-	9.9		-	15.0		-
	6	1.9		-	3.4		-	4.6		-	6.5		-	11.0		-
Mean		2.33		1.73	4.25		3.30	5.88		4.68	8.53		6.93	13.53		11.50
f_b W 1.44xx/f_b B 500 C				0.74			0.78			0.80			0.81			0.85

FIG. 1



RILEM/CEB/FIP

FIG. 2

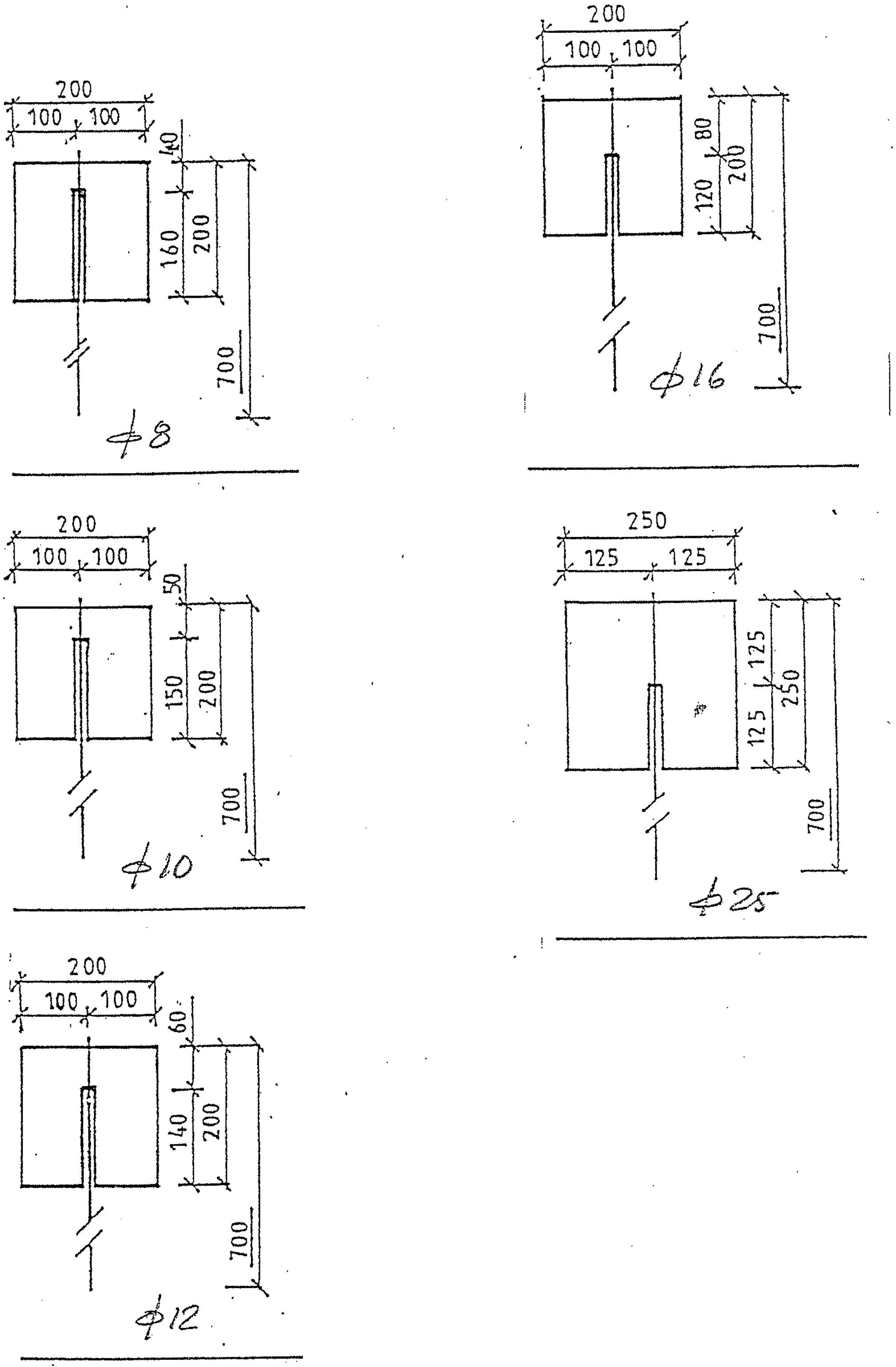
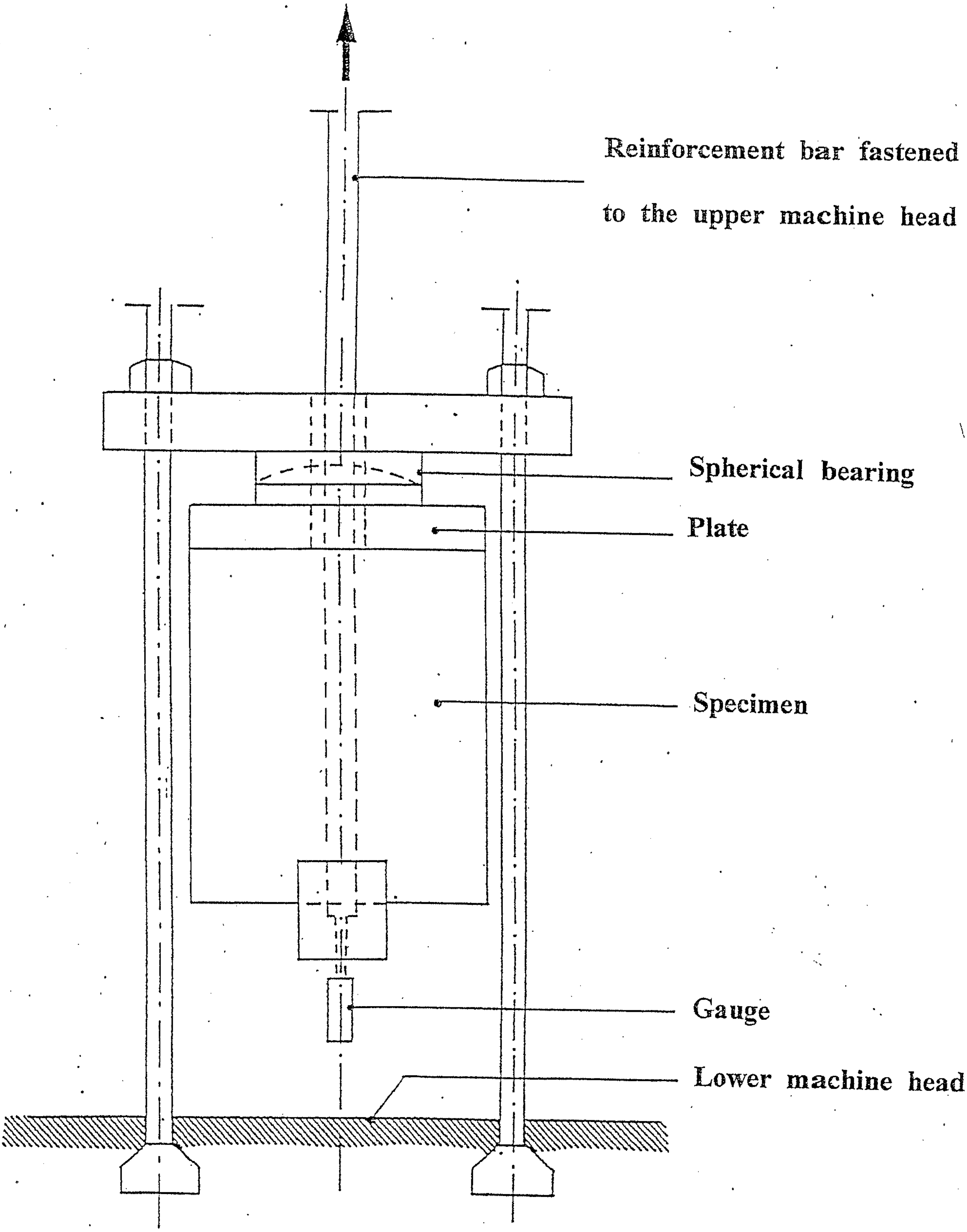

200
100
100
40
160
200
700
ϕ8
200
100
100
50
150
200
700
ϕ10
200
100
100
60
140
200
700
ϕ12
200
100
100
80
120
200
700
ϕ16
250
125
125
125
125
250
700
ϕ25

FIG. 3



Pullout testing rig in principle

FIG. 4a

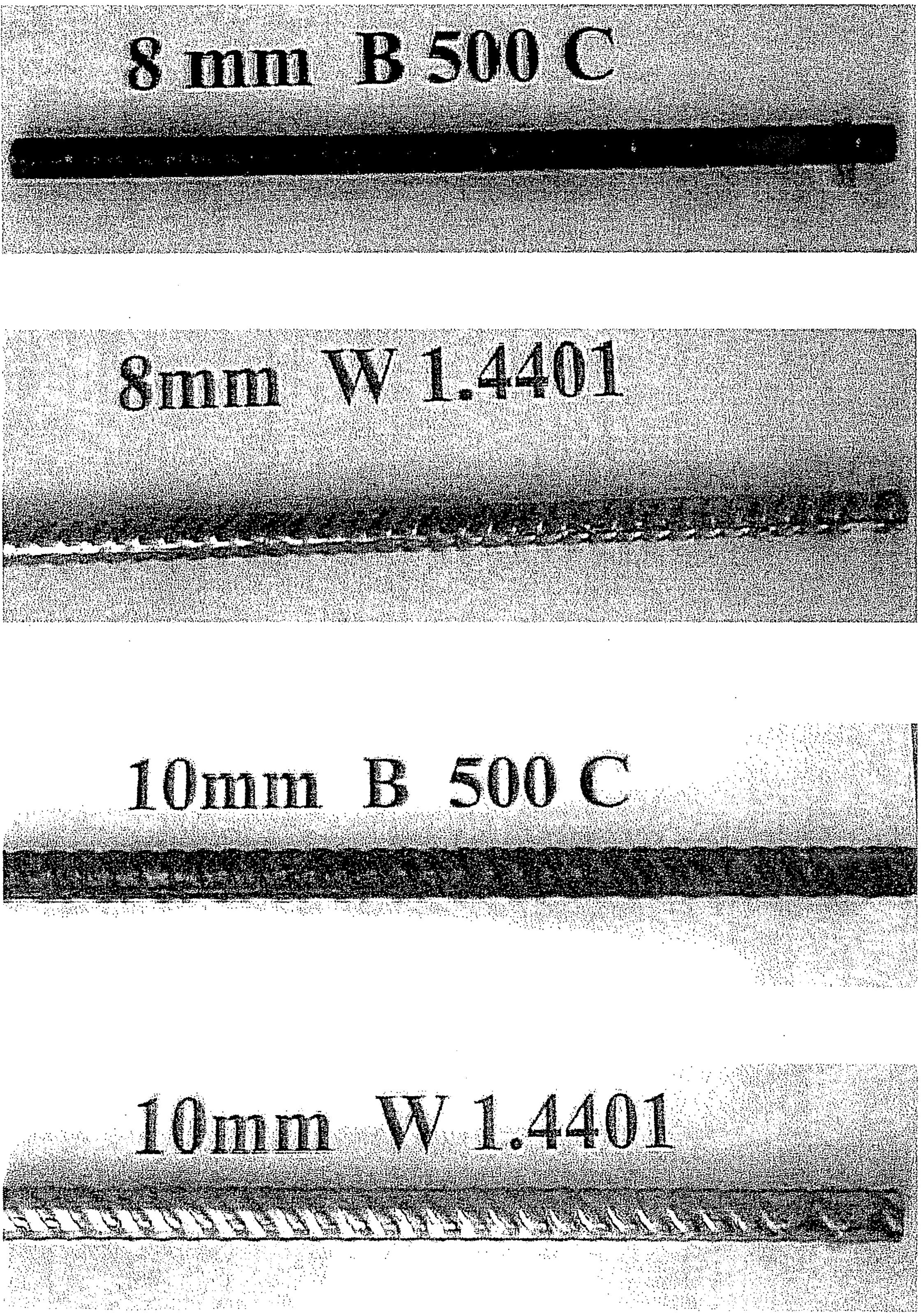


FIG. 4b

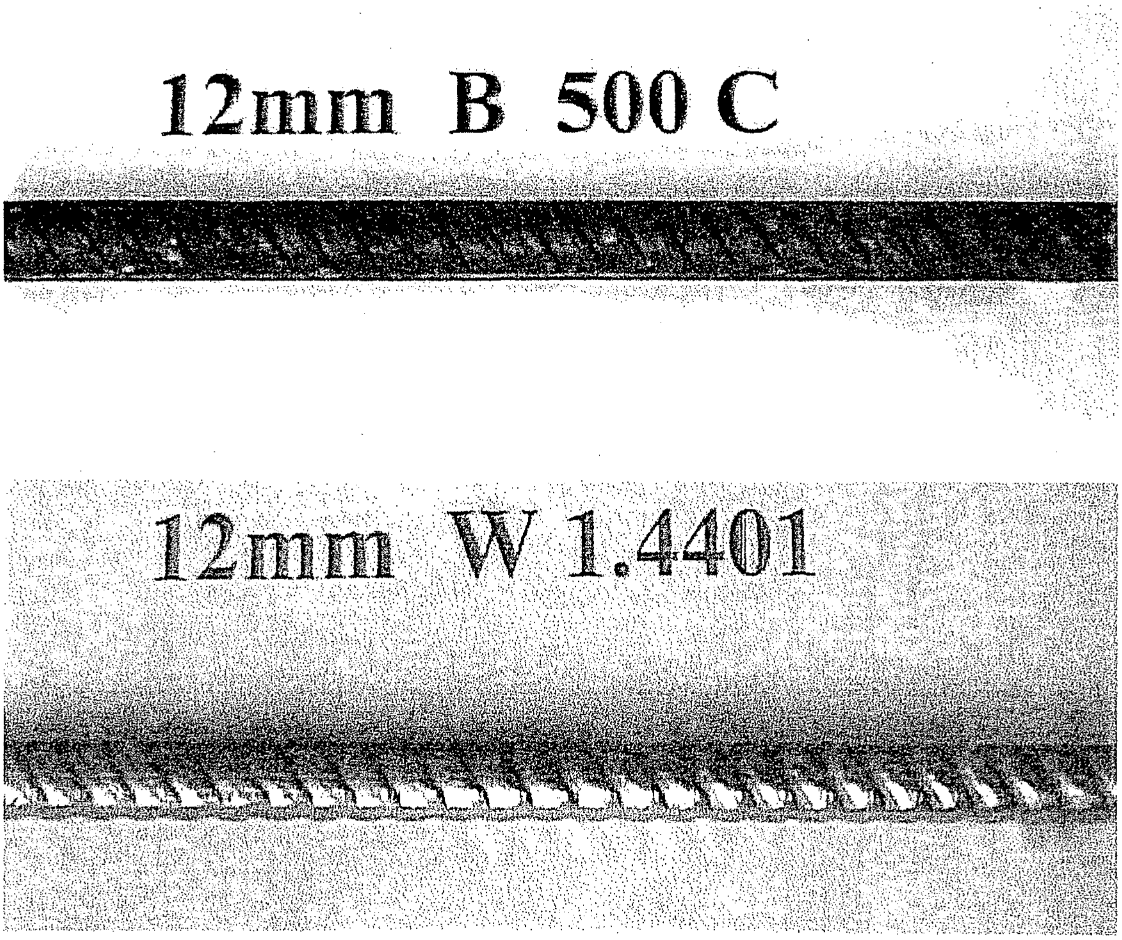
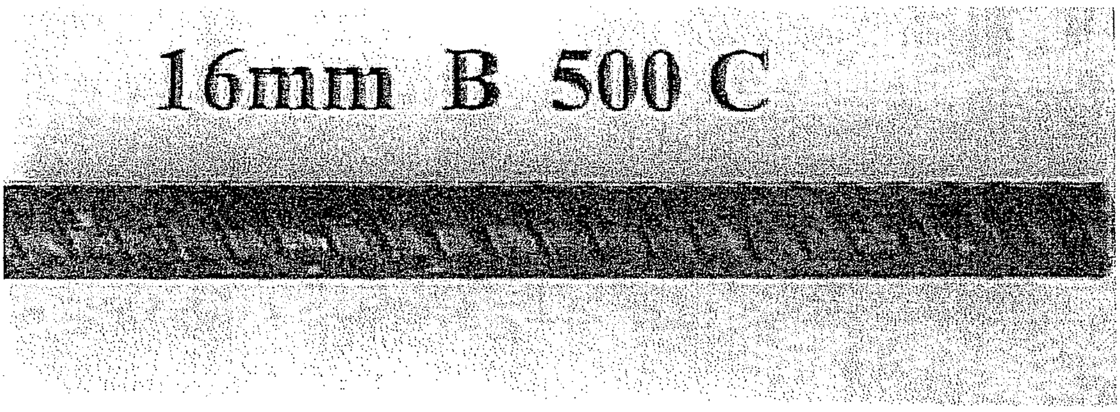


FIG. 4c



16mm W 1.4429

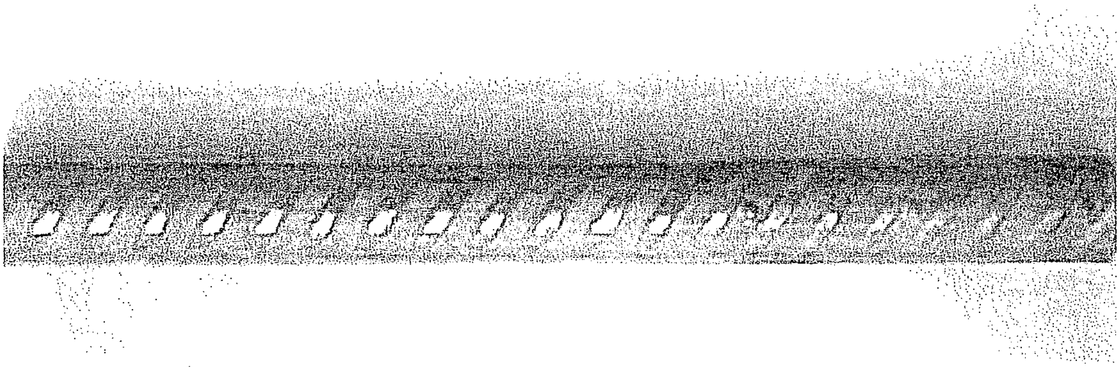


FIG. 4d

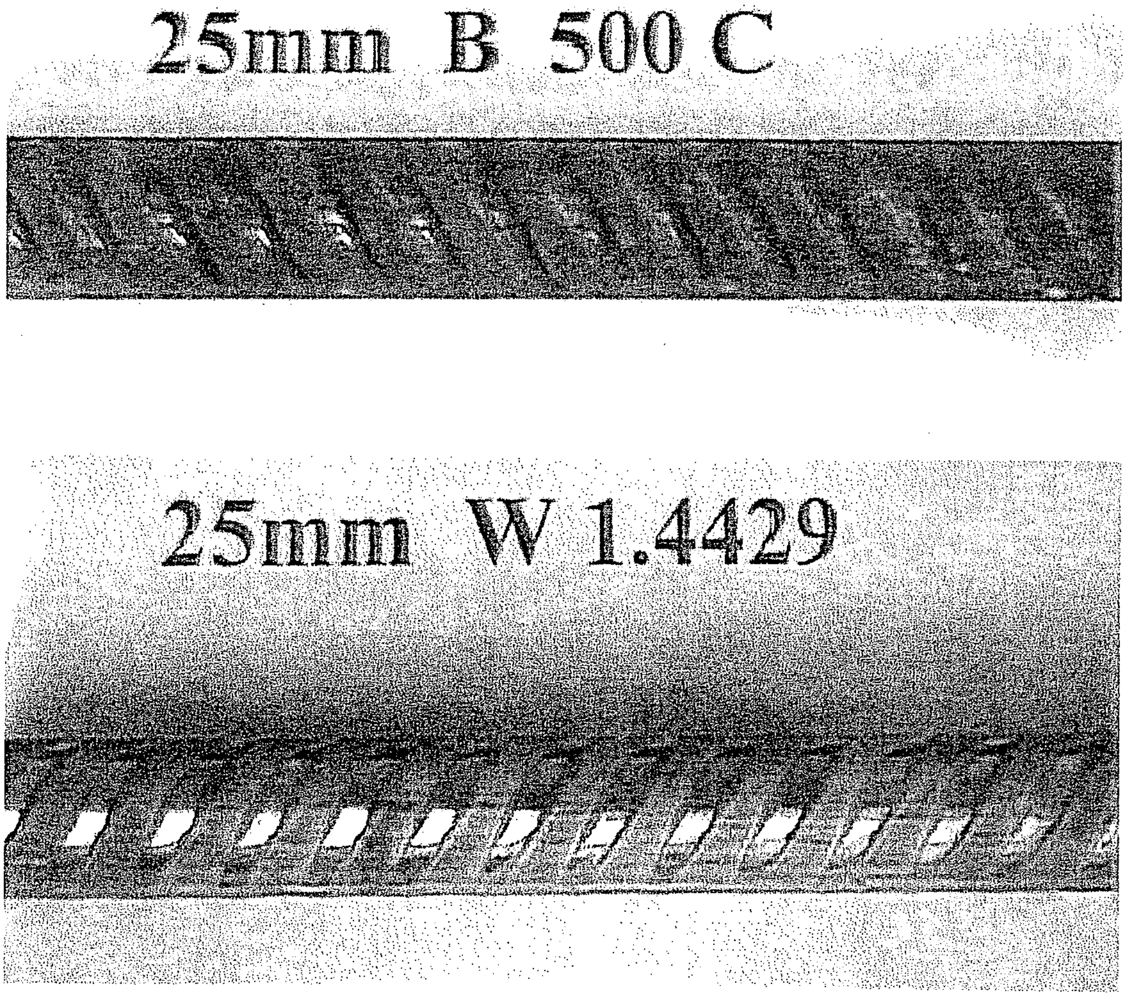


FIG. 5

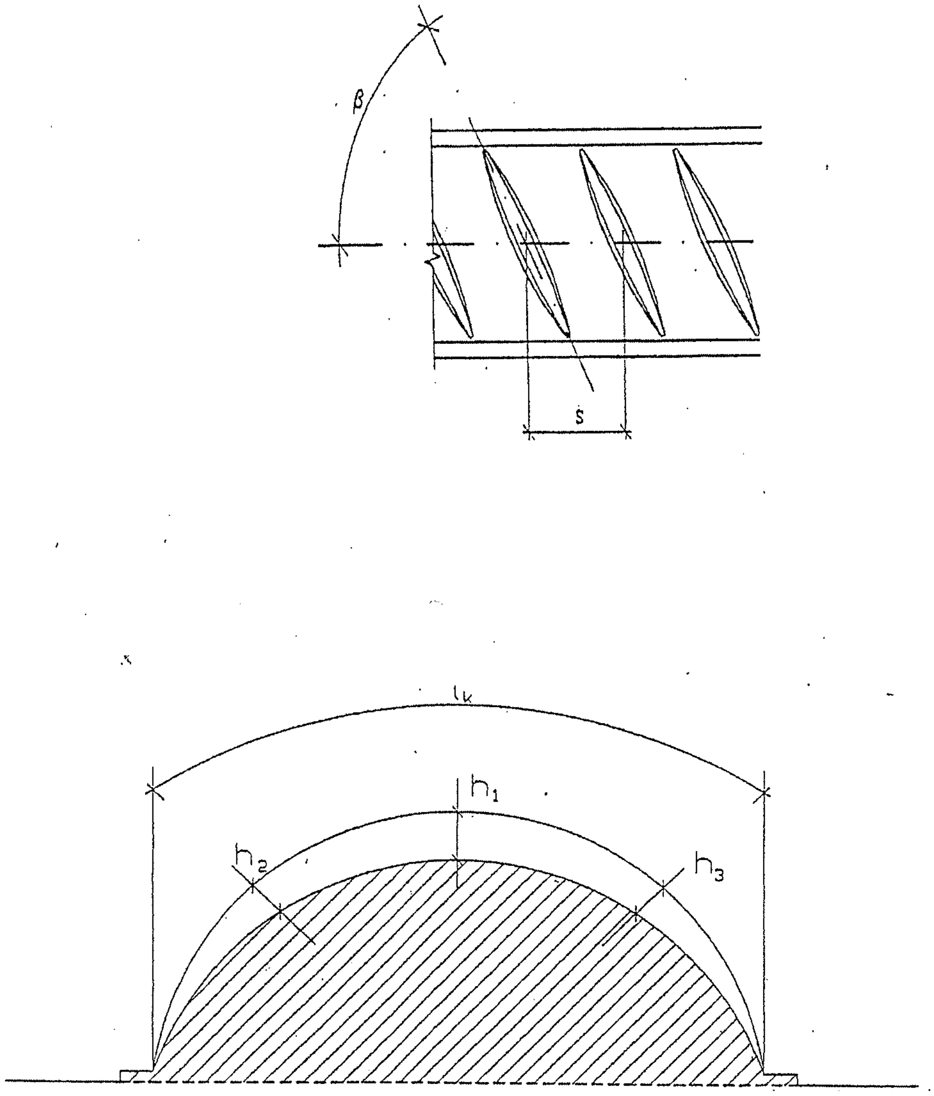


FIG. 6

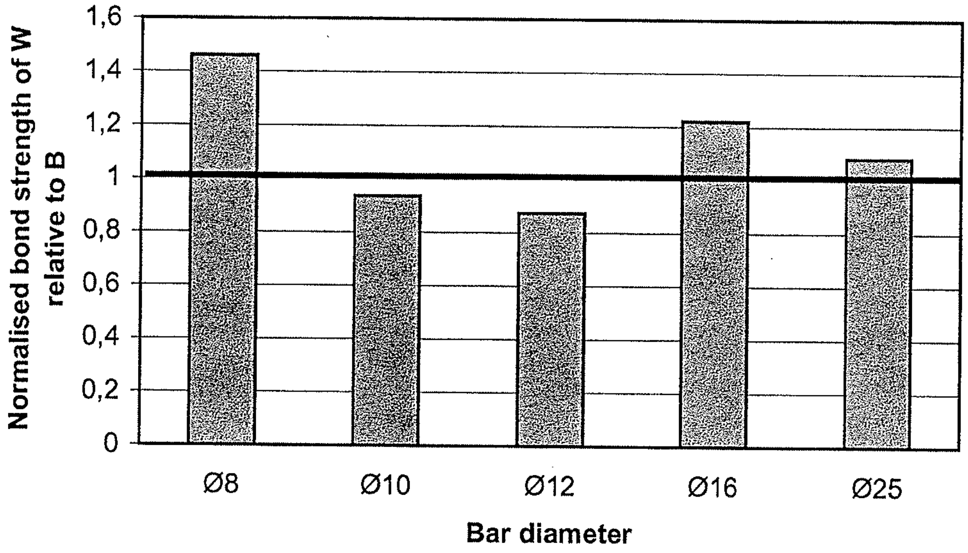


Figure 6: Bond strength normalised with respect to rib factor requirement of steinless steel (W) relative to carbon steel (B) (ref Table 7 last column)

FIG. 7

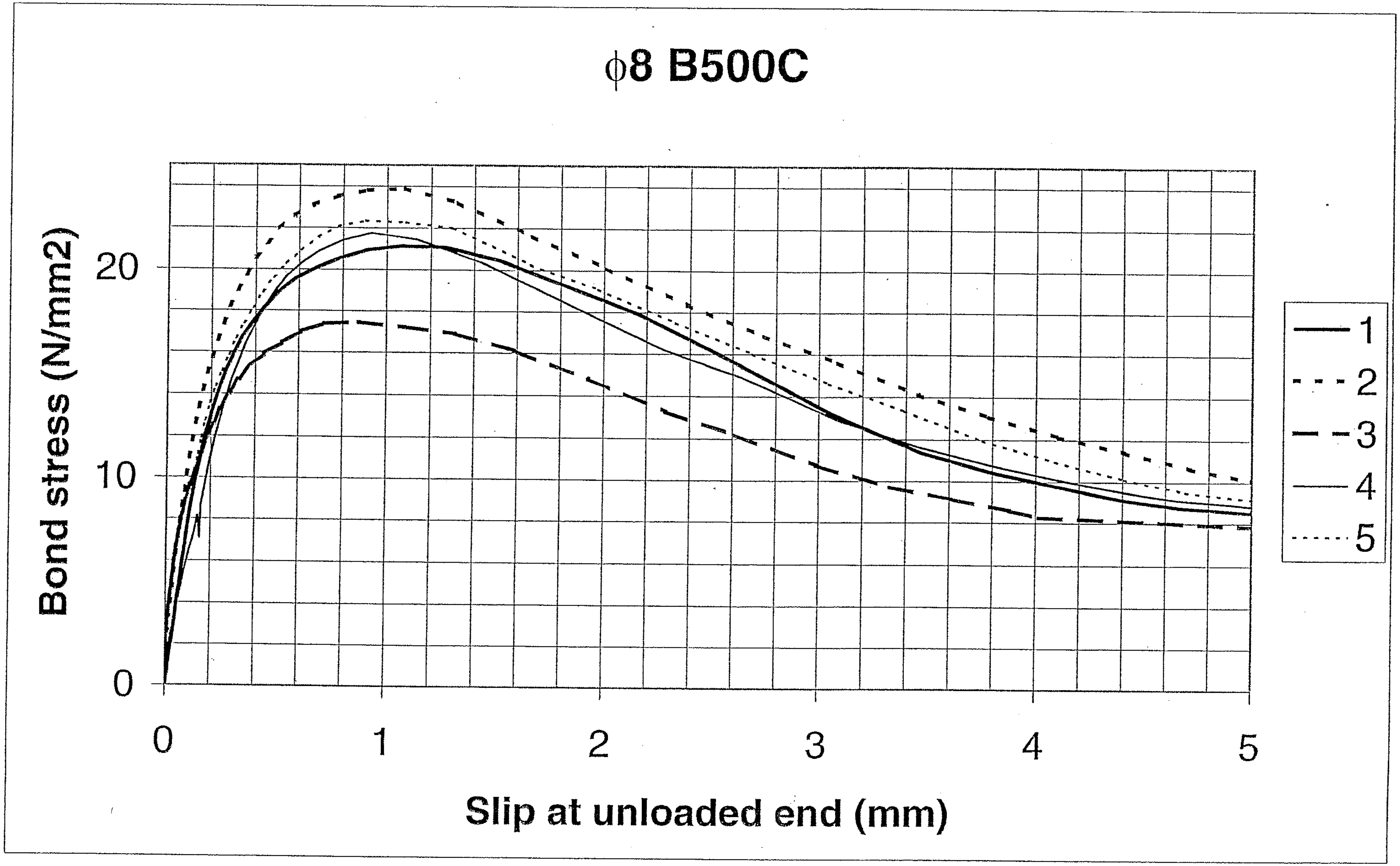
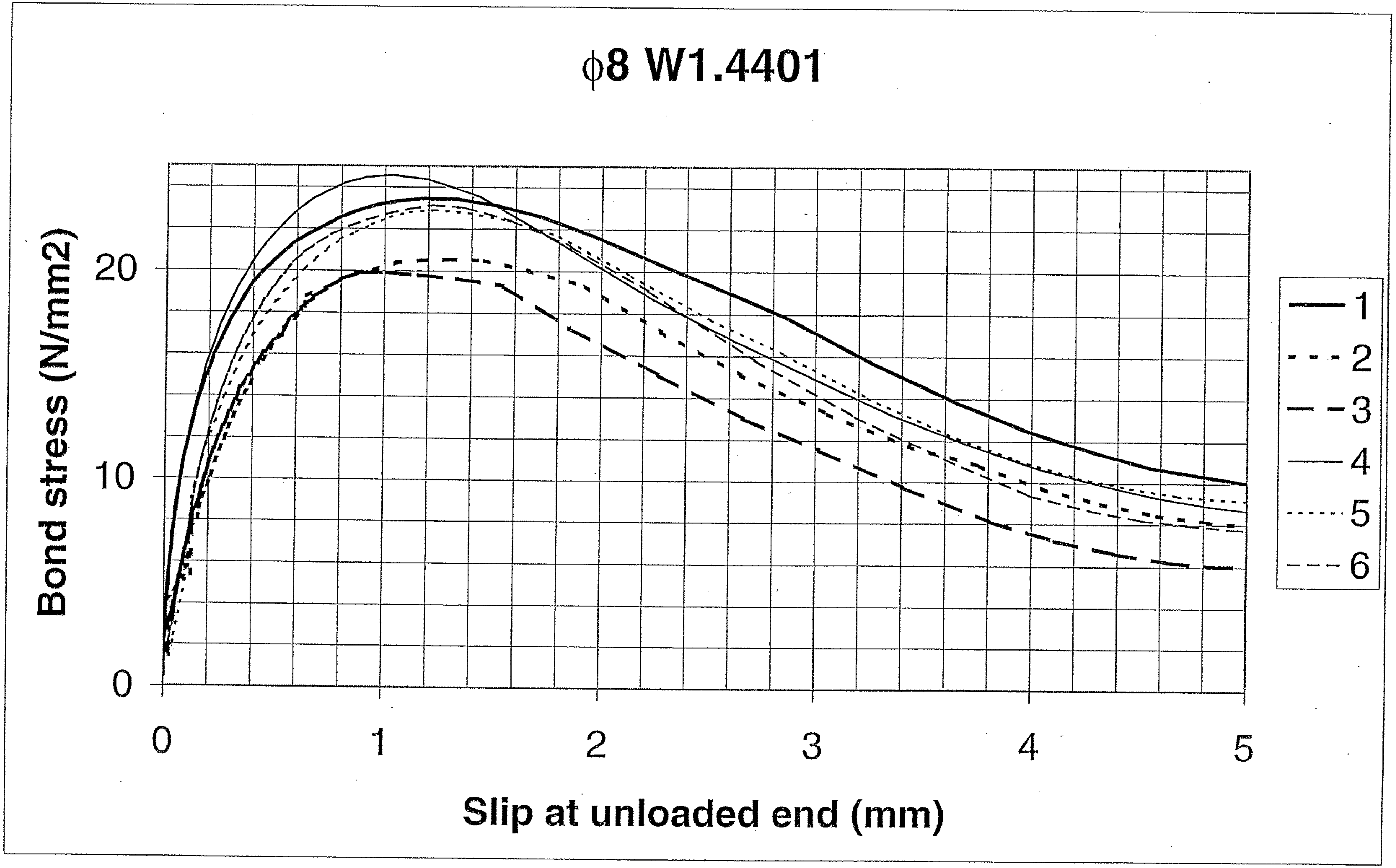

φ8 B500C
Bond stress (N/mm2)
20
10
0
Slip at unloaded end (mm)
0
1
2
3
4
5
1
2
3
4
5

FIG. 8


ϕ8 W1.4401
Bond stress (N/mm2)
0
10
20
Slip at unloaded end (mm)
0
1
2
3
4
5
1
2
3
4
5
6

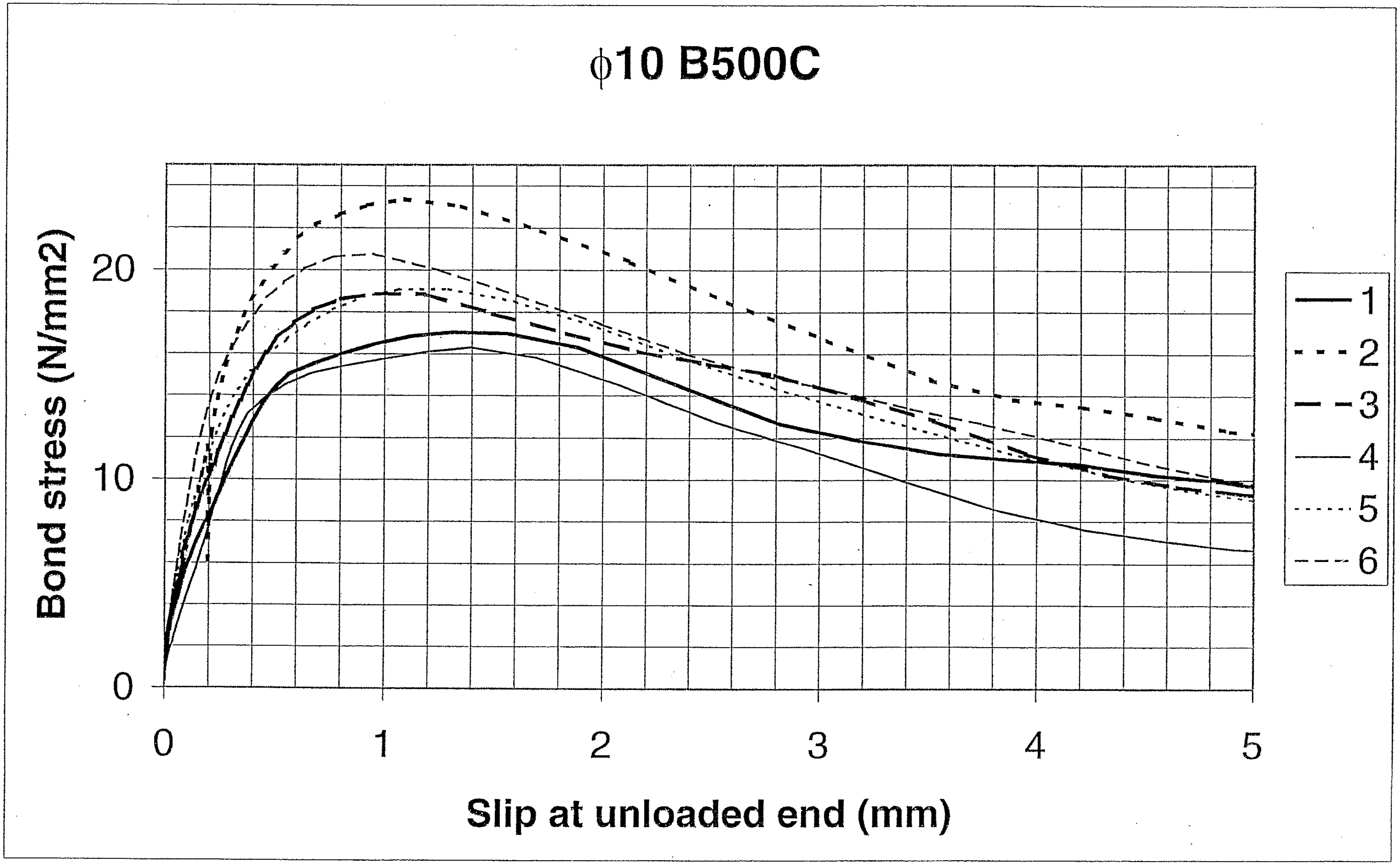
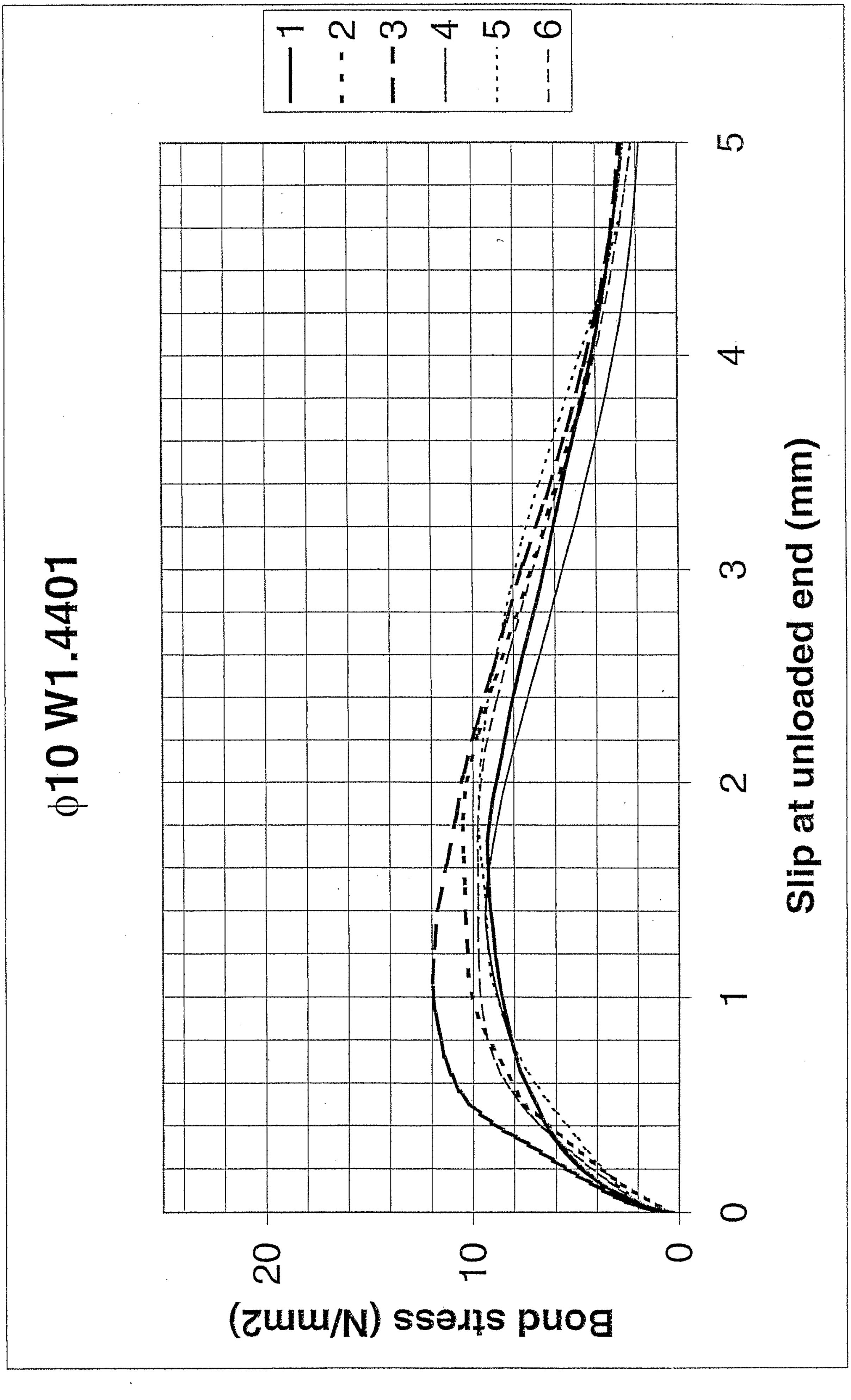

φ10 B500C
Bond stress (N/mm2)
20
10
0
0
1
2
3
4
5
Slip at unloaded end (mm)
1
2
3
4
5
6

FIG. 9

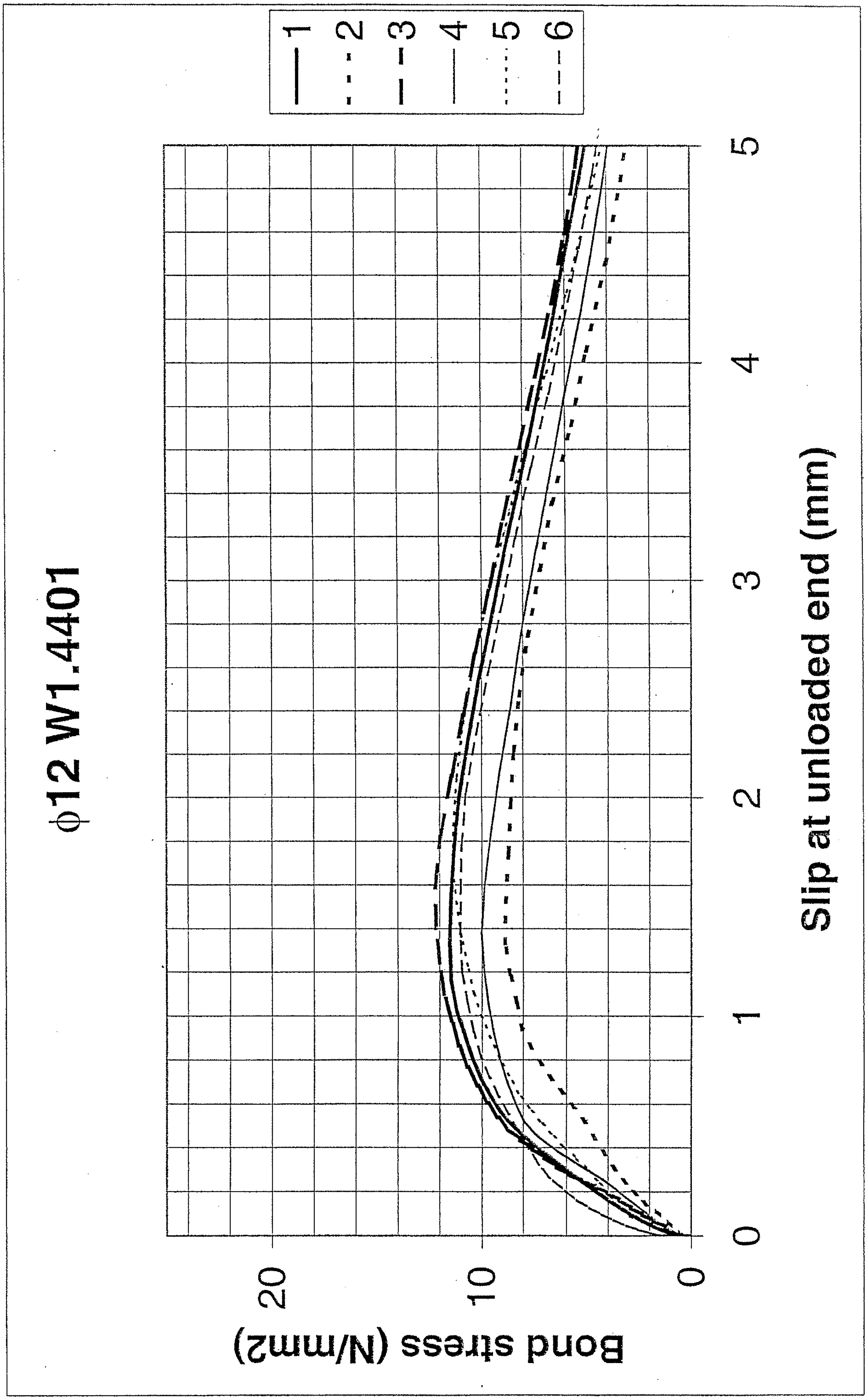
FIG. 10


ϕ10 W1.4401
1
2
3
4
5
6
Bond stress (N/mm2)
0
10
20
Slip at unloaded end (mm)
0
1
2
3
4
5


ϕ12 B500C
Bond stress (N/mm2)
0
10
20
Slip at unloaded end (mm)
0
1
2
3
4
5
1
2
3
4
5
6

FIG. 11

FIG. 12


ϕ12 W1.4401
Bond stress (N/mm2)
0
10
20
Slip at unloaded end (mm)
0
1
2
3
4
5
1
2
3
4
5
6

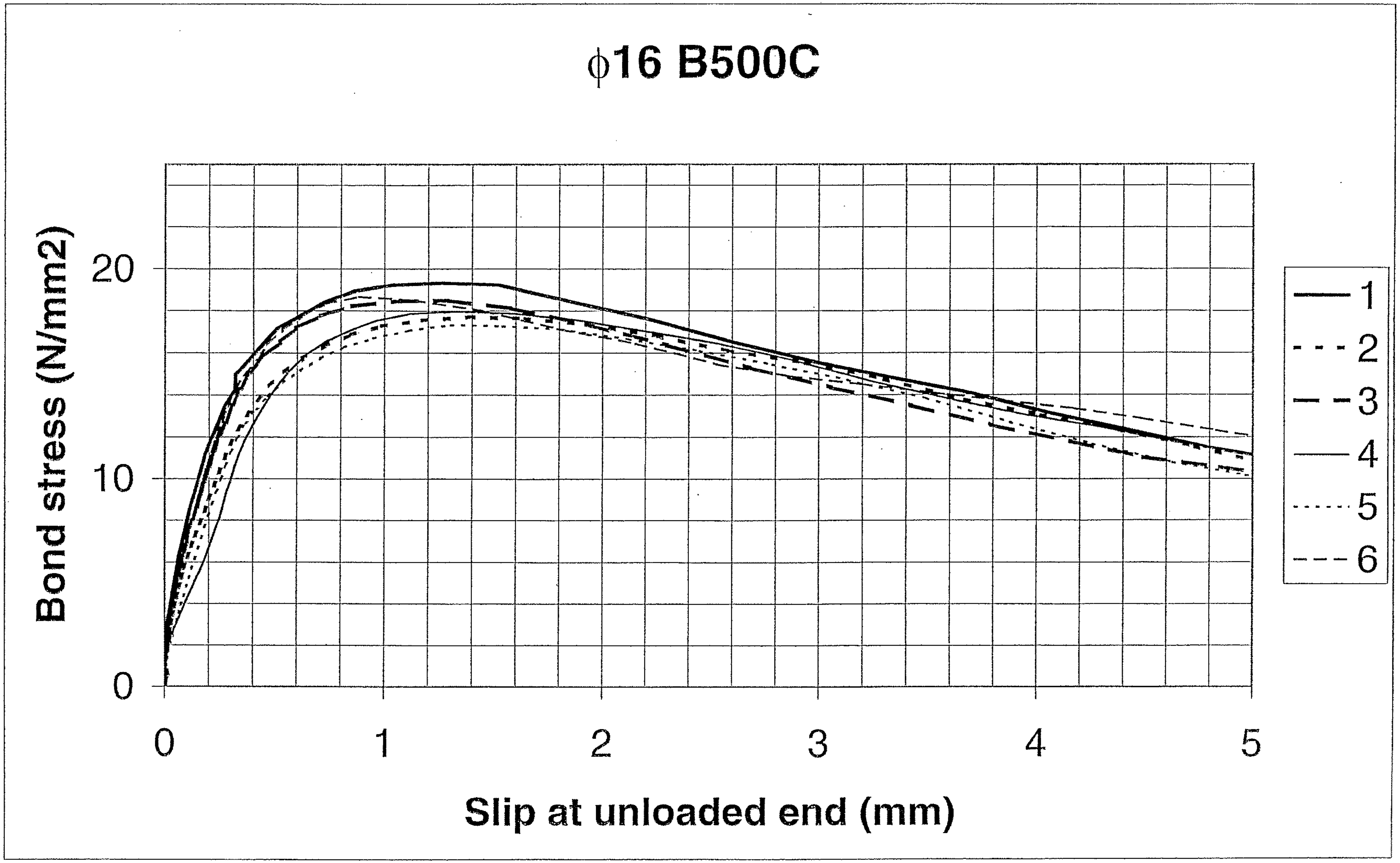

ϕ16 B500C
Bond stress (N/mm2)
0
10
20
Slip at unloaded end (mm)
0
1
2
3
4
5
1
2
3
4
5
6

FIG. 13

FIG. 14

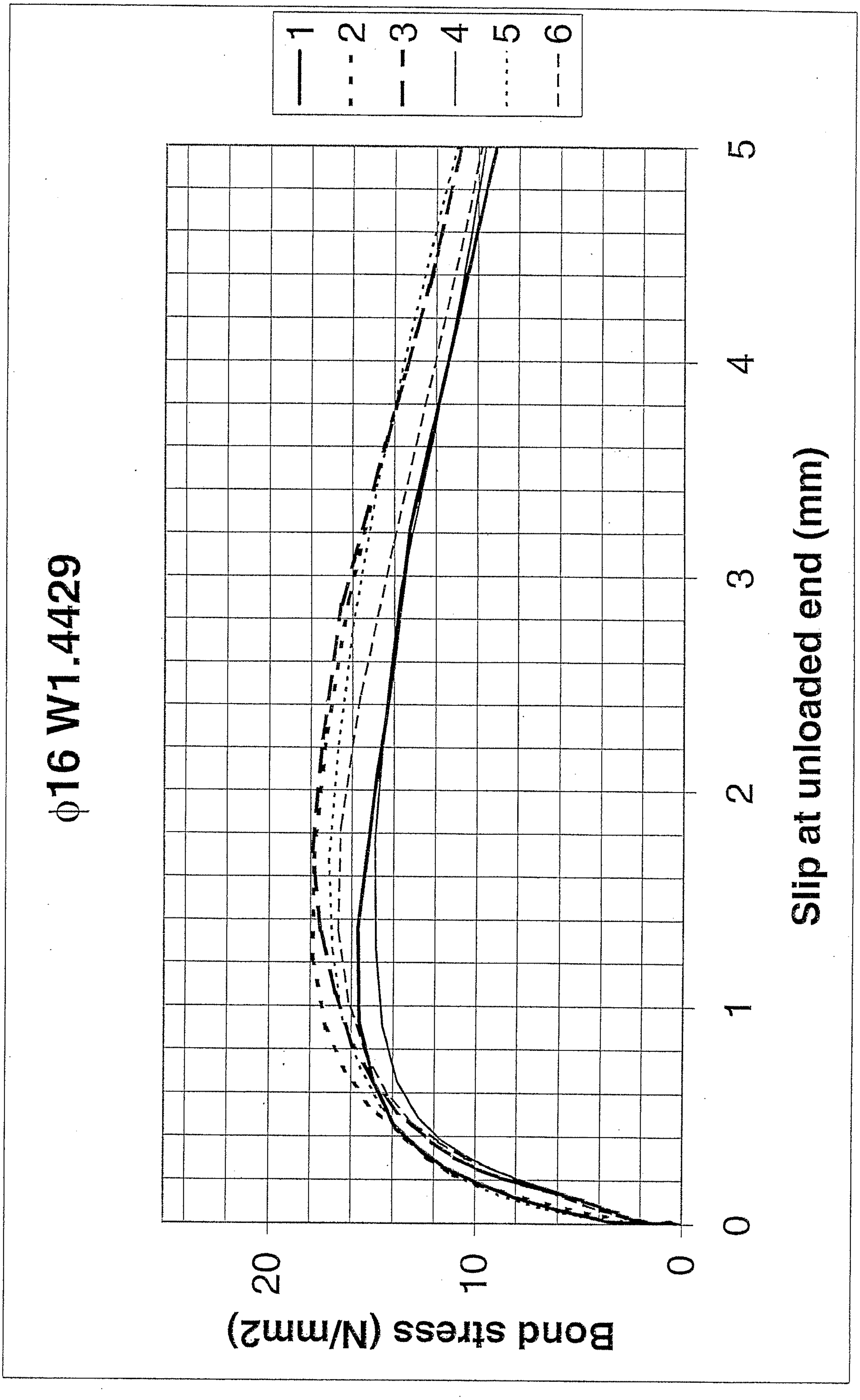

ϕ16 W1.4429
Bond stress (N/mm2)
20
10
0
Slip at unloaded end (mm)
0
1
2
3
4
5
1
2
3
4
5
6

FIG. 15

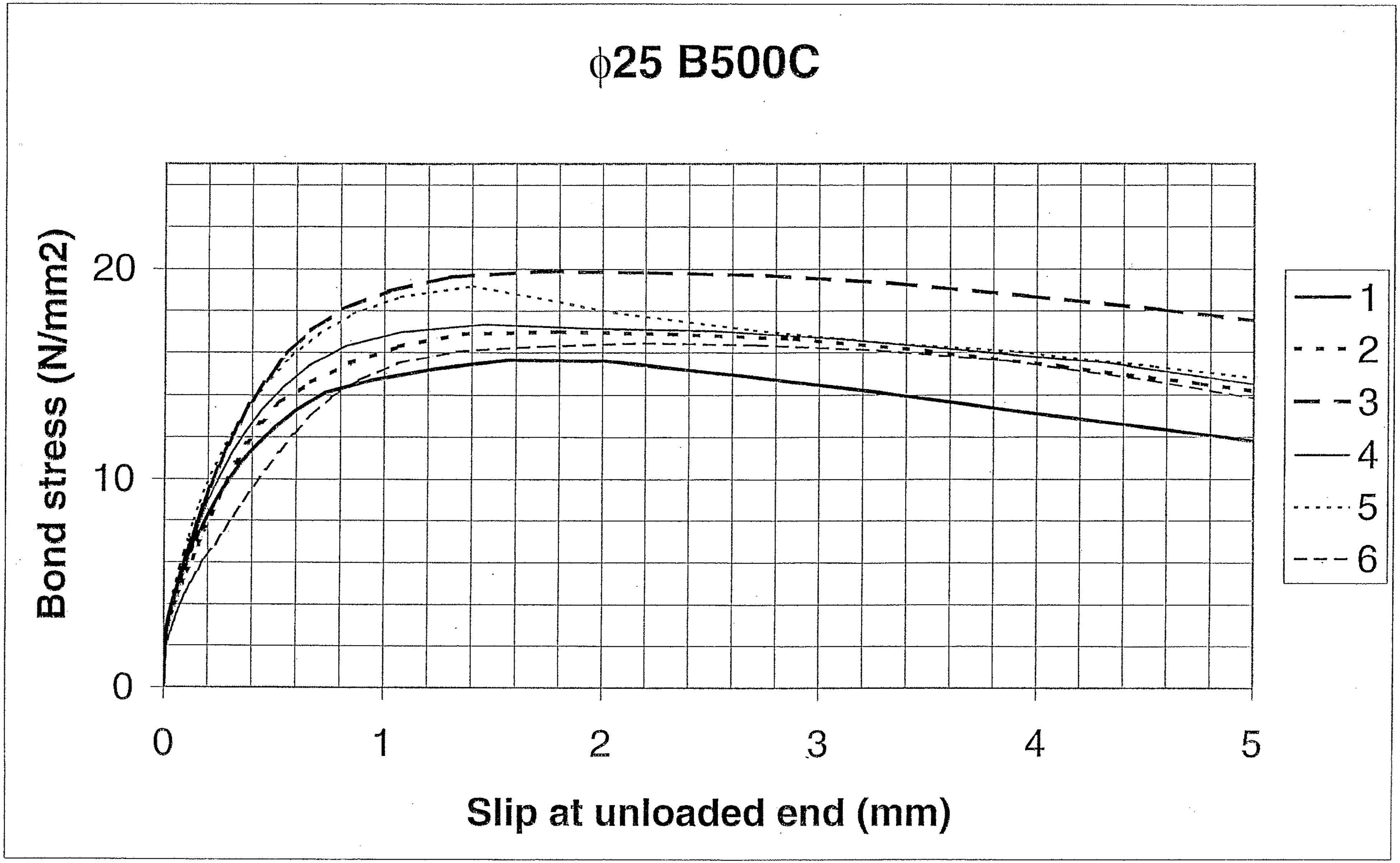
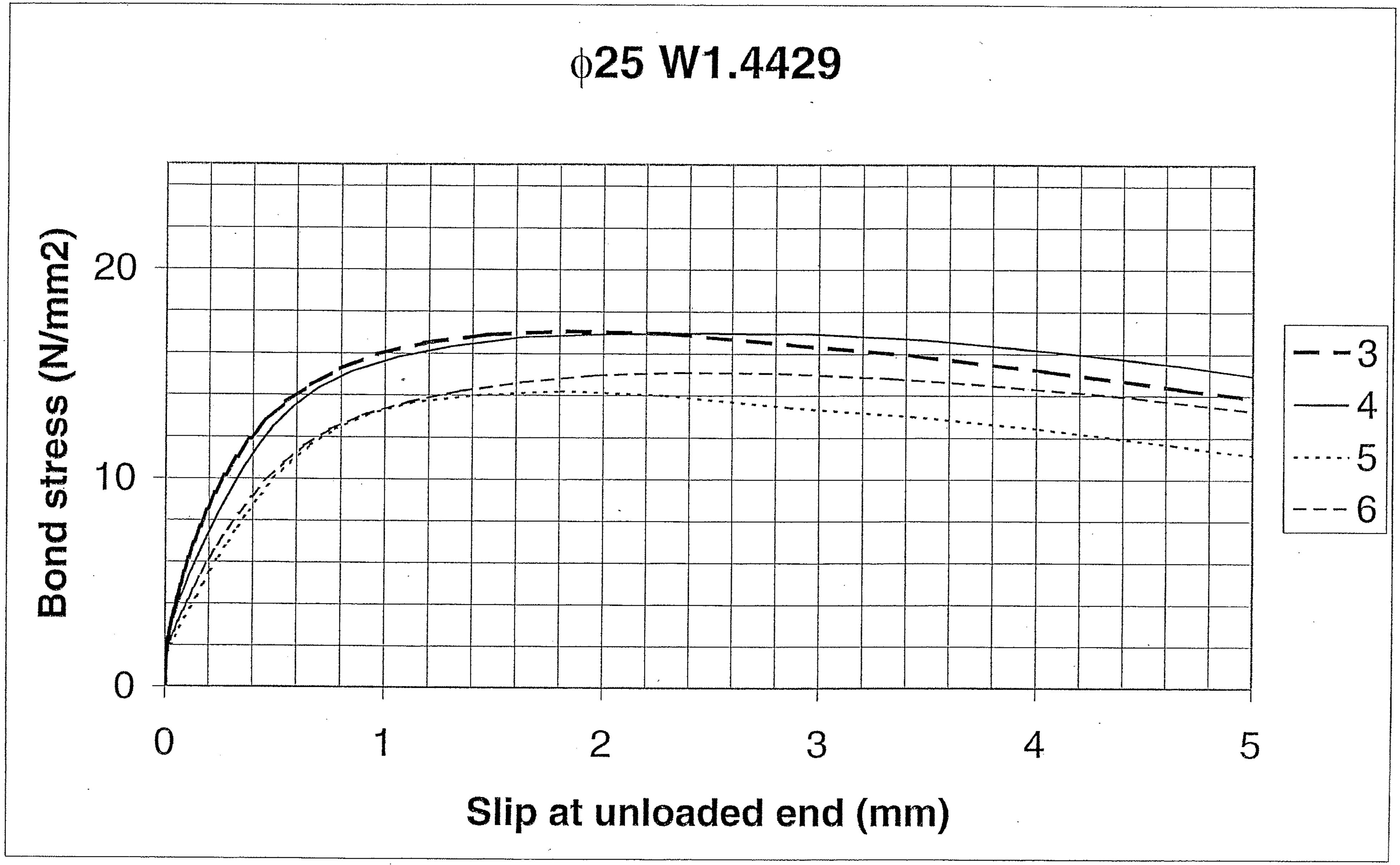

φ25 B500C

FIG. 16


ϕ25 W1.4429
Bond stress (N/mm2)
20
10
0
0
1
2
3
4
5
Slip at unloaded end (mm)
3
4
5
6

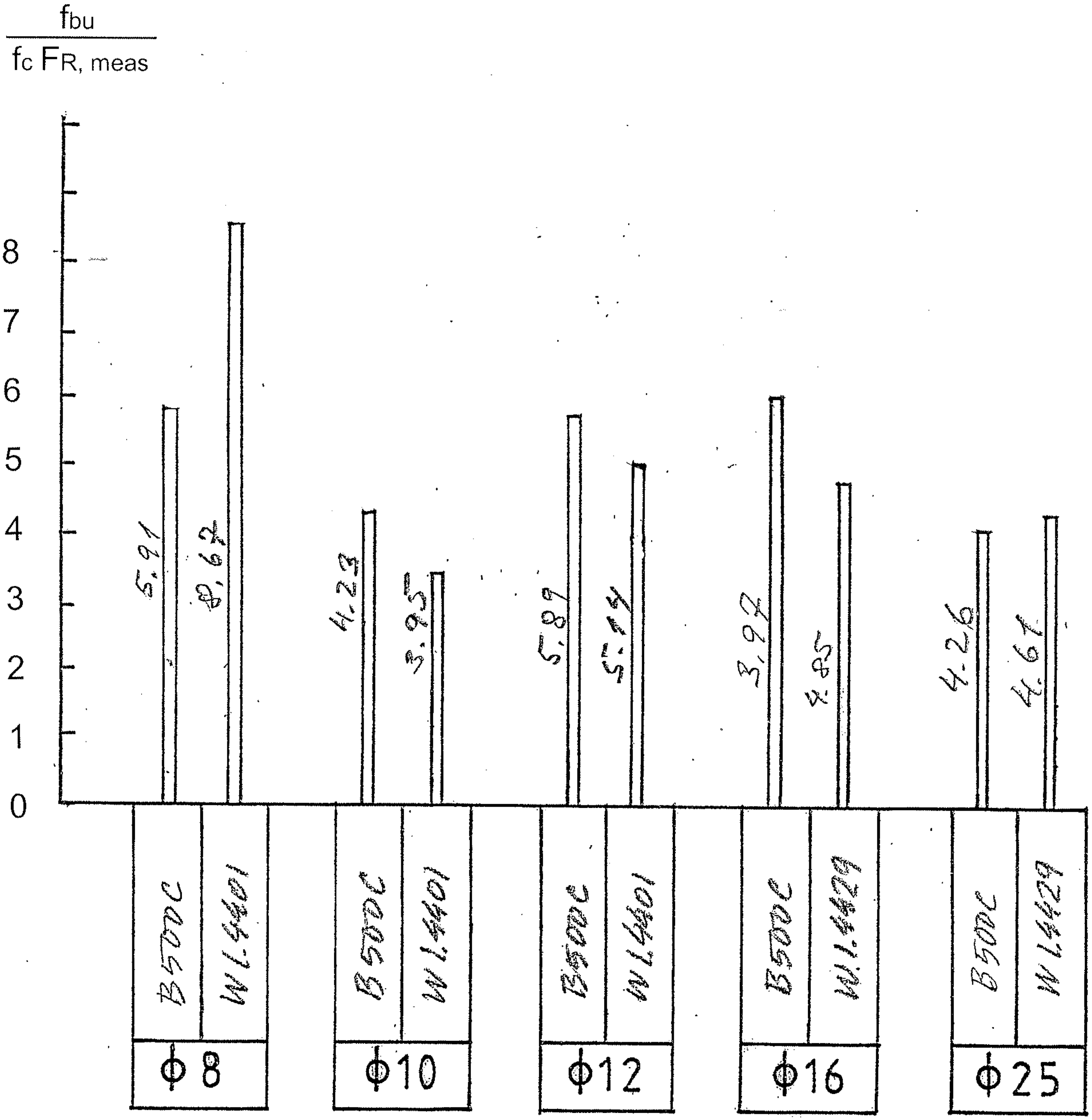
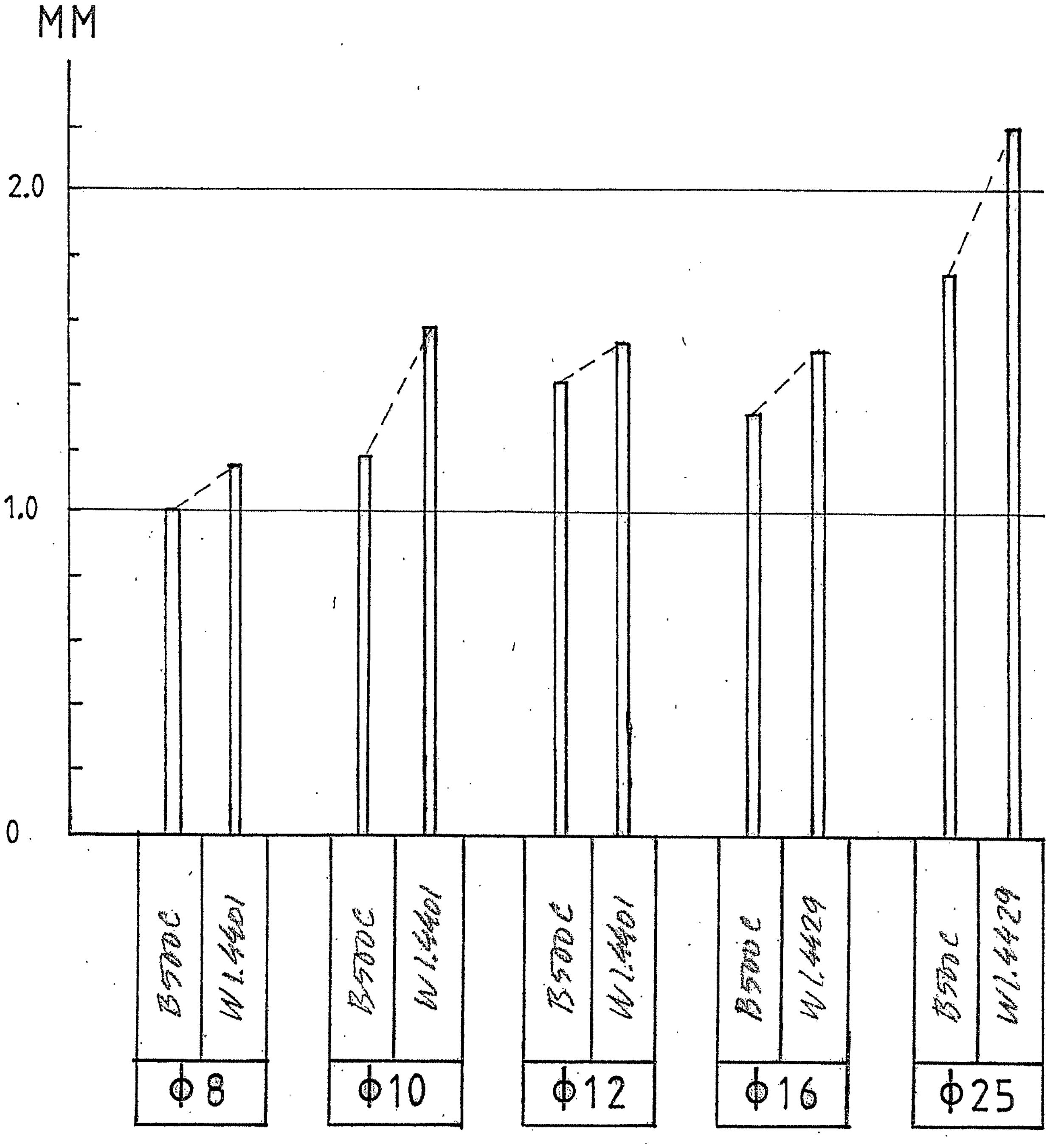

$\frac{f_{bu}}{f_c F_{R,\ meas}}$
0
1
2
3
4
5
6
7
8
5,91
8,62
4,23
3,85
5,87
5.15
3,97
4.85
4.26
4.61
B500C
W1.4401
B500C
W1.4401
B500C
W1.4401
B500C
W1.4429
B500C
W1.4429
Φ 8
Φ10
Φ12
Φ16
Φ25

FIG. 18



SLIP AT MAX LOAD