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Strengthening of Concrete Bridge Supports Using Fibre Reinforced Polymers

DN-STR-03017
December 2002

About TII

Transport Infrastructure Ireland (TII) is responsible for managing and improving the country's national road and light rail networks.

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Document Attributes

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NRA DMRB and MCDRW References

For all documents that existed within the NRA DMRB or the NRA MCDRW prior to the launch of TII Publications, the NRA document reference used previously is listed above under 'historical reference'. The TII Publication Number also shown above now supersedes this historical reference. All historical references within this document are deemed to be replaced by the TII Publication Number. For the equivalent TII Publication Number for all other historical references contained within this document, please refer to the TII Publications website.

NRA ADDENDUM TO

BD 84/02

STRENGTHENING OF CONCRETE BRIDGE SUPPORTS USING FIBRE REINFORCED POLYMERS

Standard BD 84/02 – Strengthening of Concrete Bridge Supports Using Fibre Reinforced Polymers – is applicable in Ireland with the following amendments:

GENERAL

1. The Standard provides specification requirements for use in public purchasing contracts. It does not lay down legislation requirements for products and materials used in road construction in Ireland.
2. At several locations:

For: “Overseeing Organisation”
Read: “National Roads Authority”.

SPECIFIC

1. Cover, Summary, line 2:
Delete: “the BD 48 (DMRB 3.4.7)”.
2. Contents Page, Contents, 4 Enquiries:
For: “4. Enquiries”
Read: “4. References and Enquiries”.
3. Page 1/1, Paragraph 1.2, line 3:
For: “The strengthening scheme shall comply with the requirements of BD 48 (DMRB 3.4.7).”
Read: “Requirements for strengthening shall be agreed with the National Roads Authority.”
4. Page 1/4, Paragraph 1.8, line 4:
For: “by BD 24 (DMRB 1.3.1)”
Read: “by NRA BD 24 (NRA DMRB 1.3.1).”
5. Page 2/1, Paragraph 2.4, line 1:
Delete “to resist the forces specified in BD 48”.
6. Page 2/2, Paragraph 2.11, line 1:
Delete “to BD 48”.

7. Page 3/2, Paragraph 3.7, line 7:
For: "UKAS standards"
Read: "Irish National Accreditation Board standards".
8. Page 4/1, Chapter 4:
Delete heading and text and replace with:

“4. REFERENCES AND ENQUIRIES

4.1 References

BS 5400: Steel, Concrete and Composite Bridges: Part 4: 1990: Code of Practice for Design of Concrete Bridges.

Denton, S.R., and Christie, T.J.C., "Design Charts for Strengthening Circular Concrete Columns Using FRP", *in preparation*.

NRA BD 24: Design of Concrete Road Bridges and Structures: Use of BS 5400 Part 4: 1990 (NRA DMRB 1.3.1).

4.2 Enquiries

All technical enquiries or comments on this Standard should be sent in writing to:

Head of Project Management and Engineering
National Roads Authority
St Martin's House
Waterloo Road
Dublin 4"



.....
E O'CONNOR
Head of Project Management and
Engineering

**VOLUME 1 HIGHWAY STRUCTURES:
 APPROVAL PROCEDURES
 AND GENERAL DESIGN**

SECTION 3 GENERAL DESIGN

PART 16

BD 84/02

**STRENGTHENING OF CONCRETE
BRIDGE SUPPORTS USING FIBRE
REINFORCED POLYMERS**

SUMMARY

This Standard gives requirements for strengthening bridge supports with Fibre Reinforced Polymers to meet the BD 48 (DMRB 3.4.7) vehicle impact loads. It includes design rules, advice and requirements to ensure strength and quality of installation is achieved.

INSTRUCTIONS FOR USE

This is a new Standard to be incorporated in the Manual.

1. Remove existing contents sheet for Volume 1 and insert new contents sheet for Volume 1 dated August 2002.
2. Insert BD 84/02 in Volume 1, Section 3, Part 16.
3. Archive this sheet as appropriate.

Note: A quarterly index with a full set of Volume Contents Pages is available separately from The Stationery Office Ltd.



THE HIGHWAYS AGENCY



SCOTTISH EXECUTIVE DEVELOPMENT DEPARTMENT



**WELSH ASSEMBLY GOVERNMENT
LLYWODRAETH CYNULLIAD CYMRU**



**THE DEPARTMENT FOR REGIONAL DEVELOPMENT
NORTHERN IRELAND**

Strengthening of Concrete Bridge Supports Using Fibre Reinforced Polymers

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REGISTRATION OF AMENDMENTS

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 Circular Columns

1. INTRODUCTION

Scope

1.1 This Standard presents the requirements for strengthening bridge supports to resist vehicle impact by means of fibre reinforced polymer (FRP) materials. It covers strengthening of circular, rectangular and multi-sided columns. Strengthening may be provided by fabric bonded in-situ, pre-formed laminates or pre-formed sheets.

Overseeing Organisation's Requirements

1.2 Bridge supports that fail assessment may be strengthened using FRP to increase their flexural and shear strength. The strengthening scheme shall comply with requirements of BD 48, (DMRB 3.4.7).

1.3 As FRPs remain elastic to failure, plastic methods of structural analysis shall not be used for columns strengthened using FRP.

1.4 The FRP strengthening shall be designed for a service life of 30 years. The appearance of the strengthened bridge shall be in keeping with its structural form.

Symbols

1.5 The symbols used are as follows:

A_x	area of longitudinal steel reinforcement bar number x .
d_c	the distance from the extreme compression fibre to the neutral axis (see Figure 1).
E_{wc}	elastic modulus in compression of the fibres.
E_{wt}	elastic modulus in tension of the fibres.
f_b	allowable effective bond stress.
f_{cu}	concrete cube strength.
f_{cw}	effective cube strength of the concrete in the wrapped column.
f_{yx}	stress in longitudinal steel reinforcement bar number x .

f_{wy}	compressive strength of the fibres at 'failure'.
M	ultimate applied bending moment (ie nominal applied bending moment multiplied by γ_{fl} and γ_{f3}).
M_u	ultimate bending moment capacity of the section being considered about the uncracked centroidal axis for the particular values of d_c assumed.
M_{us}	ultimate bending moment capacity of the steel reinforcement about the uncracked centroidal axis for the particular value of d_c assumed.
M_{uc}	ultimate bending moment capacity of the concrete about the uncracked centroidal axis for the particular value of d_c assumed.
M_{uw}	ultimate bending moment capacity of the axial fibres about the uncracked centroidal axis for the particular value of d_c assumed.
n	number of longitudinal steel reinforcement bars.
N	axial load coexistent with M to give the worst effect (this may be either the nominal or ultimate value).
N_u	ultimate axial load capacity of the section being considered for the particular value of d_c assumed.
N_{us}	ultimate axial load capacity of the steel in the section considered for the particular value of d_c assumed.
N_{uc}	ultimate axial load capacity of the concrete in the section considered for the particular value of d_c assumed.
N_{uw}	ultimate axial load capacity of the axial fibres in the section considered for the particular value of d_c assumed.
N_{uwt}	ultimate axial load capacity of the axial fibres in the section considered for the particular value of d_c assumed, neglecting the compressive strength of the fibres.

R_c	radius of a circular column.
R_s	effective radius to the longitudinal steel reinforcement in a circular column.
R_{wl}	mean radius to the axial fibres strengthening a circular column.
t_l	thickness of the axial fibres.
t_h	thickness of the hoop fibres.
ϵ_{cm}	compressive strain at the outermost compression fibre of the concrete at failure when failure is governed by the concrete strain capacity.
ϵ_{cp}	compressive strain at the outermost compression fibre of the concrete, which may be less than ϵ_{cm} .
ϵ_{sx}	strain in longitudinal steel reinforcement bar number x .
ϵ_{wcy}	characteristic compressive strain at 'yield' of the fibres.
ϵ_{wcm}	characteristic compressive strain capacity of the fibres.
ϵ_{wtm}	characteristic tensile strain capacity of the axial fibres.
ϵ_{wt}	peak tensile strain in the axial fibres, at the tension face.
γ_{mwE}	partial factor for the modulus of the fibres in tension and compression.
γ_{mwy}	partial factor for the compressive strength of the fibres.
γ_{mwe}	partial factor for the strain capacity of the fibres in tension and compression and the strain at 'failure' in the fibres in compression.
θ_x	angular position of longitudinal steel reinforcement bar number x (see Figure 1).
θ_{dc}	is the angular position of the neutral axis (see Figure 1).

Sign Convention

1.6 Throughout this Standard compressive strains and stresses are positive. Tensile strains and stress are negative.

The sign convention for angles is shown in Figure 1.

Definitions

1.7 The definition of terms used in the Standard are given below:

FRP: Fibre Reinforced Polymer (or Plastic) comprising high strength and elastic tensile modulus fibres in a resin matrix.

Composite: Alternative term for FRP, ie fibres plus resin. Sometimes referred to as 'advanced composite'.

Laminate: FRP composite in the form of a strip. Pultruded sections are often referred to as laminates, but the term is not specific to any form of production.

Fibre content: The volume of fibre in a laminate as a percentage of the total volume of the composite in a specific direction, usually 40-45% for wet lay-up and 60-70% for a factory produced laminate. May also be referred to as volume fraction.

Note. The properties of an FRP are significantly lower than those of the fibre from which it is made, mainly because only some of the cross sectional area consists of fibre (the rest is resin). The resin is assumed not to contribute to the strength of the FRP. An approximate conversion from fibre or fabric properties to those of the composite can be obtained by factoring by the volume fraction of fibre (this should not be relied upon for design). For example, for an FRP with a volume fraction of 65%, the modulus of the composite is approximately 0.65 times the modulus of the fibre.

Wrapping: FRP applied in layers to the surface of a bridge column, with the fibres aligned in a specified direction, eg axial or hoop.

Axial:	Wrapping with the fibres aligned with the long axis of the column, ie top to bottom.	Resin:	A resin matrix is used to impregnate the fibres and bind filaments, fibres and layers of fibre together. In a wet lay-up installation, the resin also bonds the FRP to the substrate (eg concrete). In the case of E-glass fibre, the resin is also needed to form a protective layer to prevent 'corrosion' of the fibres.
Hoop:	Wrapping with the fibres placed around the circumference of the column, at 90° to the long axis of the column.		
Fibre:	The fibres which may be used for bridge support strengthening - either organic (aramid, carbon) or glass. The organic fibres are manufactured in the form of very fine filaments (eg 12 microns diameter) which are spun and assembled together to form a yarn (many of the terms and techniques used are those of the textile industry). The yarn, or fibre, is the basic unit of FRP reinforcement. Usually, fibre properties are based on tests on dry yarn. A number of yarns (called 'ends') may be assembled to form a tow or roving (rather like a strand in rope making). The properties of a tow are based on epoxy resin impregnated strand tests.		<p><u>Notes</u></p> <p>At present only bis-phenol-A type liquid epoxy resins co-cured with amines type hardeners are permitted for bridge support strengthening carried out to this Standard, see Annex A.</p> <p>If a pultruded laminate is used, then an adhesive is needed to bond the laminate to the substrate. This is usually an epoxy resin, but bonding to a fully cured laminate requires careful selection of the adhesive to ensure compatibility even though both are epoxy resins.</p>
Fabric:	Fibres generally woven into a fabric. Fibres can be aligned in any direction - 0°, 45° and 90° are most common. Properties in a specified direction are usually expressed in terms of the dry fabric; they are lower than those of the fibre from which the fabric is made (typically by about 15%) due to the crimp effect and to the difficulty of testing the strength of dry fabric (the applied load is not uniformly distributed between all the bundles of yarn).	Confinement:	The action of the hoop fibres which delays failure of the concrete in compression by bursting or spalling.
		Pultrusion:	A factory method of manufacturing FRP laminates in long lengths. Sections currently available include plates, rods and profiles.
		Wet lay-up:	A method of installing FRP wrapping generally by hand, although machines have been developed to wrap columns semi-automatically. Dry reinforcement (fabric or tow sheet) is impregnated with resin immediately prior to application to the column (the operation is similar to hanging wallpaper).
UD fabric:	Uni-directional fabric has all the high strength fibres aligned in one direction. A small amount of transverse fibre is provided to retain the shape of the fabric. UD fabric is stronger (in the direction of the fibres) than other types.	Pre-preg:	Fibres impregnated with resin and attached to a backing paper or polymer release film. Aerospace pre-pregs require high temperature cure, but low temperature cure versions (30-40°C) are available.
Tape:	An alternative to UD fabric is a tape (sometimes called a 'tow sheet'). This consists of a layer of unidirectional fibres on a backing strip; the fibres are held aligned and straight until they are installed; then the backing strip is removed.	Voids:	Air bubbles trapped in the resin.

Primer: A low viscosity epoxy resin applied to the concrete to provide a good bond (normally stronger than the surface concrete) and a suitable surface for the FRP wrapping.

Putty: A filler, usually an epoxy resin in the form of a paste, used to fill holes and surface defects in the concrete surface.

Transmission Length: The length required to enable the ultimate tensile strength of the axial wrapping to be developed in bond between the concrete and FRP. Where outer layers are curtailed the transmission length is the length required to enable the ultimate tensile strength of the curtailed layers to be developed in bond between these layers and the adjacent layers.

Abbreviations

1.8 The following abbreviation is used in this Standard:

BS5400 : Part 4 means BS5400 : Part 4 as implemented by BD 24 (DMRB 1.3.1)

Mandatory Requirements

1.9 Sections of this Standard which are mandatory requirements of the Overseeing Organisations are highlighted by being contained within boxes. The remainder of that document contains advice and enlargement which is commended for consideration.

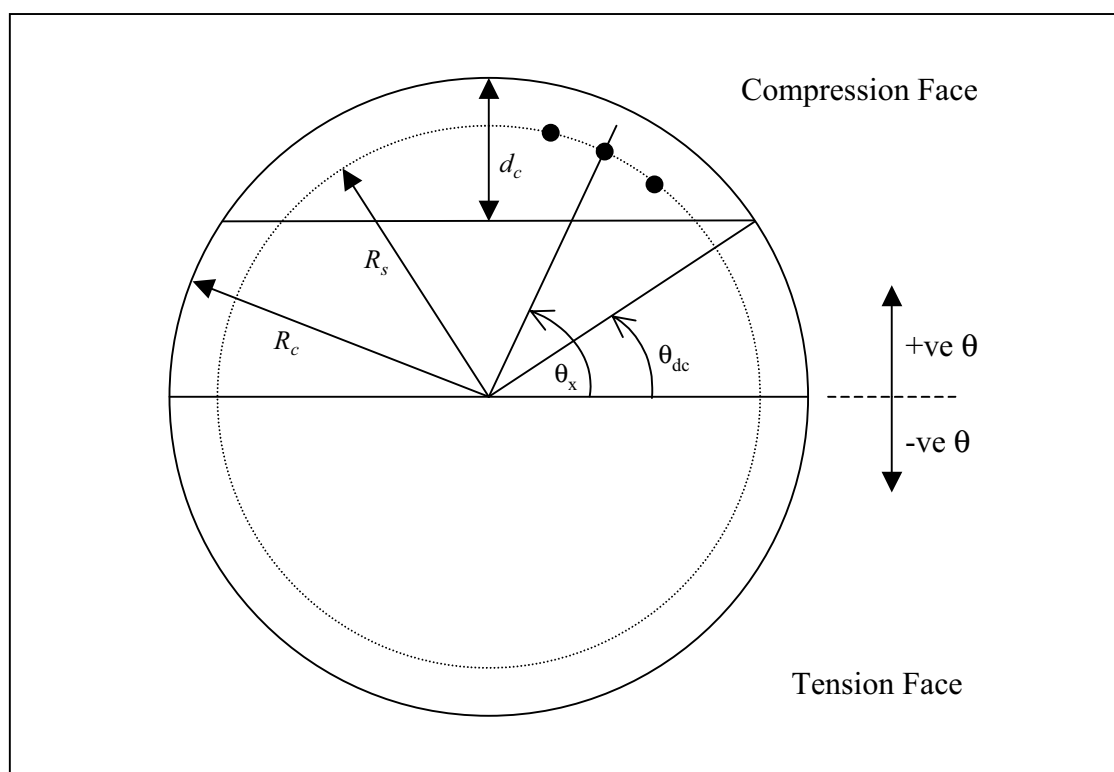


Figure 1

2. DESIGN OF FRP STRENGTHENING

Introduction

2.1 Strengthening may be required to provide some or all of the following:

- i. Increased flexural capacity.
- ii. Increased shear capacity.
- iii. An increase in the moment and/or shear capacity of the connections at the top and/or bottom of the column.
- iv. Increase in axial load capacity.

General

2.2 Throughout this Standard, reference to FRP properties is to those of the fibres in their longitudinal direction, eg area of fibres, modulus, tensile strength etc. Where fibres are used in the form of a fabric, the properties are those of the dry fabric in the specified direction.

2.3 For the purposes of this Standard the term circular column is used to include multi-sided columns where the corners are physically removed or packing is provided to form a column which is approximately circular with a radius of curvature nowhere less than 100 mm.

2.4 The design of FRP wrapping to resist the forces specified in BD 48 shall be carried out in accordance with BS 5400 Part 4, together with the method given in this Standard. Alternatively, special analysis may be used to design the FRP wrapping, provided the results are validated by tests on representative specimens, and with the agreement of the Overseeing Organisation.

2.5 Great care shall be taken to ensure that the correct material properties are used in design and construction. The properties shall be noted on the drawings and other relevant documents with details of the conditions to which they apply, eg fibre, fabric, composite, direction, method of measurement and the relationship of the design values to test results.

2.6 Partial factors for design of FRP wrapping shall be taken from Table 1.

Material	γ_{mwe}	γ_{mwe}	γ_{mwy}
Aramid fibre	1.20	1.20	1.44
Carbon fibre	1.15	1.15	1.32
Glass fibre	1.50	1.50	2.25

Table 1. Values of partial factors for FRP materials.

Note. The values of the partial factors are the same irrespective of the method of specifying the property, eg in terms of the fibre, fabric or composite laminate. Background to these partial factors is included in Annex A.

Fibre types are given in alphabetical order, no preference is implied. However, carbon fibres may perform less well under impact. Where carbon fibres are to be used, consideration should be given to providing additional aramid or glass fibre layers (ie a hybrid material).

2.7 For circular columns circumferential (hoop) FRP wrapping can be used to:

- i. increase the concrete compressive strength
- ii. increase the compressive strain in the outermost fibre of the concrete at failure
- iii. increase the shear capacity
- iv. enable the compressive strength of the axial FRP to be used in design.

Circumferential (hoop) FRP shall satisfy the following requirements:

- A minimum of two layers of FRP hoop fibres shall be provided.
- An overlap shall be provided at all joins so that the FRP effectively acts as a continuous hoop. An overlap of 200 mm or more may be assumed to satisfy this requirement.
- Where axial and hoop FRP is applied to a column, hoop FRP shall be placed over axial.

2.8 Where the FRP wrapping consists of a pre-formed laminate in sections, fitted around the column and attached by filling the gap with grout, the hoop strength of the FRP shall be neglected unless one of the following is provided.

- i. A minimum of two layers of hoop wrapping, continuous around the circumference and installed, in accordance with 2.7, over the full length of the sections, or
- ii. Test data to demonstrate that the joints between sections can provide the hoop strength assumed in the design over their full length.

2.9 The following design equations for circular columns with FRP strengthening have been validated by tests on columns strengthened with UD fabric of UTS = 2,360 MPa and modulus (E) = 104 GPa (mean values from tests). The equations may be used for other types of fibre, provided the fibre properties are within the following limits:

- (i) Tensile strain to failure greater than 1.2% and less than 5%.
- (ii) Elastic modulus (E) greater than 70 GPa and less than 250 GPa.

Strengthening schemes which rely on fibres with properties outside these ranges may be used provided the design is validated by tests on representative specimens, and with the agreement of the Overseeing Organisation.

2.10 Experimental evidence suggests that as the thickness of FRP is increased the average ultimate stress that can be developed in the FRP reduces. In order for the axial fibre to be fully effective the following expression should be satisfied:

$$E_{wt} \text{ (GPa)} \varepsilon_{wtm} t_f \text{ (mm)} \leq 2.37$$

Where t_f is the thickness of fibre.

Design for axial force and bending moment

2.11 FRP strengthening to BD 48 may be based on standard design code equations for reinforced concrete, modified to include the contribution of the FRP. In this case, the fibres are treated as additional reinforcement (the strength of the resin is neglected).

FRP provides additional axial force and bending moment capacity by:

- i. Increasing the area of longitudinal (axial) tension reinforcement.
- ii. Increasing the area of longitudinal (axial) compression reinforcement.
- iii. Confining the concrete in the compression zone, preventing the cover concrete from spalling (bursting), increasing its strain capacity and enhancing its compressive strength.

The provision of circumferential (hoop) FRP to confine the concrete and increase its strain capacity can significantly improve the efficiency of the strengthening design for axial force and bending moment by increasing the strain that can be developed in the axial FRP.

2.12 If circumferential (hoop) FRP is provided over the full length of the axial FRP in accordance with Clause 2.7 and if it has a stiffness in the direction at 90° to the long axis of the column such that:

$$\frac{t_b E_{wt}}{R_{wl} \gamma_{mwE}} > 320 \text{ MPa} \quad (1)$$

then

- i. The compressive strength of wrapped, ie confined, concrete to be used in the calculation of bending moment capacity, f_{cw} , may be assumed to be 1.5 times the cube strength, f_{cu} , but not more than 80 MPa.
- ii. ε_{cm} may be assumed to be 0.01.
- iii. The compressive strength of the FRP may be used in the design for axial force and bending moment.

2.13 For rectangular and multi-sided columns which do not comply with the provisions of Clause 2.3 (ie not “approximately” circular):

- i. The compressive strength of axial FRP shall be taken to be zero except on the basis of tests either on an unsupported laminate similar to the proposed wrapping, or on a wrapped column.

- ii. The enhancement of concrete strength and strain to failure due to confinement by hoop fibres shall be taken to be zero, except on the basis of test data from representative specimens and with the approval of the Overseeing Organisation.

2.14 The strain in the concrete, reinforcement and FRP shall be derived from the assumption that plane sections remain plane.

2.15 Axial fibre shall be provided with an adequate transmission length beyond the point at which it is no longer required. The transmission length may be taken as

$$\frac{E_{wt} \epsilon_{wtm}}{f_b} t$$

where t is the thickness of axial fibre being curtailed and f_b is the allowable effective bond stress between the curtailed FRP and the concrete (or the continuing FRP where appropriate). Shorter transmission lengths may be used provided they can be demonstrated experimentally.

Alternatively an adequate transmission length can be achieved by extending the axial fibre 250mm beyond this point and providing a band of two layers of hoop FRP wrapping. These provisions are not required where the end of the axial wrapping is enclosed within a collar satisfying the requirements of Clauses 2.21 to 2.23.

2.16 The ultimate axial force and bending moment capacities of an FRP strengthened column about the centroid axis, for a particular value of d_c and a given peak compressive strain in the concrete, may be expressed as follows:

$$N_u = N_{uc} + N_{us} + N_{uw} \quad (2)$$

$$M_u = M_{uc} + M_{us} + M_{uw} \quad (3)$$

The contributions due to the concrete (N_{uc} , M_{uc}) and the steel (N_{us} , M_{us}) may be determined in accordance with BS 5400 Part 4 based on the neutral axis depth, d_c , of the strengthened column. Alternative concrete properties may however be used when confinement

(see Clause 2.7) is provided to enhance the concrete strength and compressive strain in the outermost fibre of the concrete at failure. The design equations set out in Clause 2.17 may be used to account for these effects in circular columns.

The contribution due to the FRP (N_{uw} , M_{uw}) may be determined assuming that the FRP is elastic to failure in tension. It may, however, fail in compression.

2.17 FRP strengthening for circular columns may be designed using either the following method or the design charts in Annex B.

The design procedure to obtain the area of axial fibre needed to provide the total required ultimate bending moment capacity equal to M , with given coexistent applied ultimate axial load N , is given below. (It should be noted that, as an increase in axial load may be beneficial, the most severe combination of M and N may occur with the minimum ie nominal value of N)

- i. Propose a thickness of axial fibres¹. (It is assumed that axial fibres are placed in layers of even thickness all round the column)
- ii. Assume that the strain in the outermost compression fibre of the concrete, ϵ_{cp} , is equal to ϵ_{cm} .
- iii. Determine (by iteration or otherwise) the value of d_c that gives an axial load capacity of the strengthened column equal to the applied axial load, N , (see Equations 2,5,7 and 10). Any limitations on the tensile strain capacity of the FRP should be ignored at this stage.
- iv. Calculate the ultimate bending moment capacity of the strengthened column for this value of d_c (see Equations 3, 6, 8 and 11)
- v. If the ultimate bending moment capacity is less than the ultimate applied bending moment, M , increase the thickness of axial fibre and repeat from (iii) until the bending moment capacity equals or exceeds the applied bending moment.
- vi. Determine the maximum tensile strain in the axial fibre ϵ_{wt} from Equation 14. If ϵ_{wt} is less than its maximum permissible value (given by $\epsilon_{wtm}/\gamma_{mwe}$) then the axial fibre thickness is adequate.

¹ Even if the design chart method is not used, the charts can be used at this stage to determine an approximate thickness of axial fibres.

vii. If, however, ϵ_{wt} exceeds $\epsilon_{wtm}/\gamma_{mwe}$ then the concrete in the outermost compression fibre of the column will reach ϵ_{cp} before the outermost tensile axial fibre reaches its maximum permissible tensile strain. This situation has to be reversed and there are two alternative procedures to follow depending upon whether ϵ_{cp} is equal to or greater than 0.0035.

viii. If ϵ_{cp} is **greater than 0.0035**, then the tensile strain in the FRP may be reduced as follows:

- Reduce ϵ_{cp} from its current value to a lower value not less than 0.0035.
- Determine the corresponding enhanced concrete strength. Reducing ϵ_{cp} may also reduce the enhancement in compressive strength that can be achieved. For columns satisfying the requirements of Clause 2.12, f_{cw} may be assumed to vary linearly with ϵ_{cp} from f_{cu} at a strain of 0.0035 to $1.5 f_{cu}$ at a strain of 0.01.
- Repeat from (iii) using these revised values of ϵ_{cp} and f_{cw} .

ix. If ϵ_{cp} is **equal to 0.0035**, then the procedure is as follows:

- Increase the axial fibre thickness and vary the value of d_c until the axial load capacity of the column, as defined in Equation 2, is equal to the applied axial load N .
- Determine ϵ_{wt} from Equation 14.
- If ϵ_{wt} is still higher than $\epsilon_{wtm}/\gamma_{mwe}$, then repeat from (a) until the maximum tensile strain in the axial fibres is equal to or less than its maximum permissible value.

In order to calculate the axial and moment capacities in (iii) and (iv) above, the individual contributions of the reinforcement, concrete and axial FRP may be calculated using the following expressions.

Reinforcement

The contribution of the steel reinforcement is calculated as follows:

With reference to Figure 1, the strain in reinforcement bar number x is given by:

$$\epsilon_{sx} = (R_s \sin \theta_x - R_c + d_c) \frac{\epsilon_{cp}}{d_c} \quad (4)$$

The stress, f_{yx} , in reinforcement bar no. x , is calculated from Figure 2 of BS 5400 Part 4.

The axial load capacity and bending moment capacity of the longitudinal steel reinforcement (taking moments about the diameter) are given by:

$$N_{us} = \sum_{x=1}^n f_{yx} A_x \quad (5)$$

$$M_{us} = \sum_{x=1}^n f_{yx} A_x R_s \sin \theta_x \quad (6)$$

Concrete

The axial load capacity and bending moment capacity of the concrete (taking moments about the diameter) are given by:

$$N_{uc} = 0.6 \frac{f_{cw}}{\gamma_{mc}} R_c^2 \left(\frac{\pi}{2} - \theta_{dc} - \frac{\sin 2\theta_{dc}}{2} \right) \quad (7)$$

$$M_{uc} = 0.6 \frac{f_{cw}}{\gamma_{mc}} \frac{2}{3} R_c^3 \cos^3 \theta_{dc} \quad (8)$$

where

$$\theta_{dc} = \sin^{-1} \left(1 - \frac{d_c}{R_c} \right) \quad (\text{See Figure 1}) \quad (9)$$

FRP

The axial load capacity and bending moment capacity of the FRP wrapping (taking moments about the diameter) are given by:

$$N_{uw} = 2 \frac{E_{wc}}{\gamma_{mwE}} \epsilon_{cp} \frac{R_{wl} t_l}{d_c} \left[(d_c - R_c) (\theta_{\epsilon_{wcy}} - \theta_{d_c}) - R_{wl} (\cos \theta_{\epsilon_{wcy}} - \cos \theta_{d_c}) \right] \\ + 2 \frac{f_{wy}}{\gamma_{mwy}} R_{wl} t_l (\theta_{\epsilon_{wcm}} - \theta_{\epsilon_{wcy}}) \quad (10)$$

$$M_{uw} = 2 \frac{E_{wc}}{\gamma_{mwE}} \epsilon_{cp} \frac{R_{wl}^2 t_l}{d_c} \left[\frac{R_{wl}}{2} (\theta_{\epsilon_{wcy}} - \theta_{d_c}) - \frac{R_{wl}}{4} (\sin 2\theta_{\epsilon_{wcy}} - \sin 2\theta_{d_c}) - (d_c - R_c) (\cos \theta_{\epsilon_{wcy}} - \cos \theta_{d_c}) \right] \\ - 2 \frac{f_{wy}}{\gamma_{mwy}} R_{wl}^2 t_l (\cos \theta_{\epsilon_{wcm}} - \cos \theta_{\epsilon_{wcy}}) \quad (11)$$

$$- 2 \frac{E_{wt}}{\gamma_{mwE}} \epsilon_{cp} \frac{R_{wl}^2 t_l}{d_c} \left[\frac{R_{wl}}{2} \left(\frac{-\pi}{2} - \theta_{d_c} \right) + \frac{R_{wl}}{4} \sin 2\theta_{d_c} + (d_c - R_c) \cos \theta_{d_c} \right]$$

where

$$\theta_{\epsilon_{wcy}} = \sin^{-1} \left(\frac{1}{R_{wl}} \left(\frac{d_c \epsilon_{wcy}}{\gamma_{mwE} \epsilon_{cp}} + R_c - d_c \right) \right) \quad (12)$$

$$\theta_{\epsilon_{wcm}} = \sin^{-1} \left(\frac{1}{R_{wl}} \left(\frac{d_c \epsilon_{wcm}}{\gamma_{mwE} \epsilon_{cp}} + R_c - d_c \right) \right) \quad (13)$$

If the compressive yield strain of the FRP is not reached in the section then $\theta\epsilon_{wcy}$ should be taken as $\pi/2$ and if the maximum compressive strain of the FRP is not reached then $\theta\epsilon_{wcm}$ should be taken as $\pi/2$.

The maximum tensile strain in the wrapping is:

$$\epsilon_{wt} = \frac{\epsilon_{cp}}{d_c} (R_{wl} + R_c - d_c) \quad (14)$$

Design for shear capacity

2.18 Circumferential (hoop) FRP satisfying the requirements of Clause 2.7 may be used to increase the shear capacity of circular columns. Separate requirements are to be developed for other column shapes.

2.19 The shear capacity of the strengthened circular columns shall be determined by summing the contributions made by the concrete, the reinforcement and the circumferential FRP. The shear capacity of the concrete and reinforcement shall be determined in accordance with BS5400 Part 4 neglecting the axial FRP and any enhancement in concrete strength due to confinement. However, the 0.4 factor in the second expression of Clause 5.3.3.2, Table 7, shall be deleted. The contribution of the circumferential FRP to the shear capacity, V_w , is given by

$$V_w = 0.004 \left(\frac{\pi}{2} \right) \frac{E_{wt}}{\gamma_{mwE}} t_h d \quad (15)$$

where d is taken to be the depth from the extreme compression fibre to the centroid of the tension reinforcement.

2.20 The longitudinal tensile forces associated with shear at a section, must be carried by the axial reinforcement. These are additional to forces due to bending and axial load. Adequate axial reinforcement and FRP shall be provided to sustain these additional tensile forces.

This requirement may be satisfied by ensuring that the reinforcement in the column and axial FRP extend a distance of half the overall depth of the section (R_c for a circular column) beyond the point

at which it is no longer required for bending. Alternatively, the thickness of FRP required to resist the ultimate applied bending moment and coexistent axial load should be increased by the following factor:

$$1 + \left| \frac{V}{2N_{uwt}} \right|$$

where V is the shear force due to the ultimate loads and N_{uwt} is the axial load capacity of the FRP wrapping, determined when evaluating the thickness of FRP required to resist the ultimate bending moment and coexistent axial load, but neglecting any contribution due to the compressive strength of the FRP.

If strengthening is required for shear only (ie if no axial FRP is required to strengthen the column to resist the ultimate bending moment and coexistent axial load) then:

- i. The area of each axial reinforcing bar between the tension face and the mid-depth of the section shall be reduced, for bending only, by an area equal to:

$$\frac{V}{2n(f_y / \gamma_{ms})}$$

where n is the total number of effective axial reinforcing bars within this region in the section being considered.

- ii. The ultimate bending capacity of the column with this reduced area of reinforcement shall be checked to ensure it has adequate capacity to sustain the ultimate applied bending moment and coexistent axial force. Axial FRP shall be provided beneath the hoop FRP to strengthen the column, if required.

Connections at the top and bottom of the Column

2.21 If strengthening is required at the column/base connection or the connection between the column and the cross-head or deck (or within the transmission length of these connections) a collar or plinth shall be provided to strengthen this connection.

The collar or plinth shall be of sufficient strength to carry the applied loads without assistance from the FRP. It shall be at least 500 mm high and shall overlap the FRP wrapping by at least 500 mm. Appropriate details, including the provision of drips, sealants etc, shall be provided to prevent the ingress of water into the interface between the FRP and the concrete.

2.22 Collars or plinths at the column base shall be constructed of in-situ concrete. They shall be structurally connected to the base and extend up to ground level or above.

2.23 Collars at the top of columns shall be constructed of concrete or steel (or other materials with the approval of the Overseeing Organisation) and shall be structurally connected to the cross-head or deck. Care shall be taken to ensure that stress concentrations do not act on fibres where they emerge from collars.

3. FRP MATERIAL SPECIFICATION AND INSTALLATION

Introduction

3.1 It is important that all those involved (designer, contractor, fibre and resin suppliers, specialist installer, inspector) understand the basis on which properties are specified.

3.2 Detailed specification of the component materials in an FRP system and installation procedure requires specialist knowledge. Care shall be taken to ensure that the materials used are compatible. A supplier/installer with relevant expertise and trained, directly employed operatives, shall be appointed to carry out the work. The contract shall make clear where responsibilities lie. In particular, the supplier/installer shall take responsibility for the specified properties being achieved by the installed material, including the bond to the existing concrete.

3.3 The designer shall assess the condition of the existing column to ensure that it is sound and to consider the risk of future corrosion of the steel reinforcement. The need for additional measures to prevent water ingress after wrapping, eg at the top of the column, shall also be considered. Where necessary, remedial measures shall be carried out before the FRP wrapping is installed.

Material specification

3.4 Only aramid, carbon or glass fibres with strain to failure $>1.2\%$ are permitted. This figure excludes partial material factors.

Note. A description of potentially suitable FRP materials is given in Annex A.

3.5 Only epoxy resins are permitted. Careful formulation of the resin is required to achieve all of the required properties and expert advice should be sought.

3.6 The mechanical properties of the FRP shall be specified in a way that ensures that the properties of the installed material match those used in design. The properties shall be confirmed by tests on samples of laminates installed on site, under the same conditions and using the same materials and procedure as for the strengthening. At present it is not possible to specify test procedures. The supplier/installer shall provide evidence of suitable tests on their products and be able to advise on test procedures, and the properties to be achieved on site. The designer shall check that the values agreed will provide adequate design strength. The frequency of testing, number of tests, the test procedures, the properties to be measured and the required values shall be agreed between the Supplier/Installer and the Client's representative. The following general procedures shall be adopted:

- i. FRP properties: Where installation is by the wet lay-up process, sample laminates shall be made up on a flat sheet or board placed alongside the bridge supports. Tensile tests shall be carried out on coupons taken from the sample laminates to determine the ultimate tensile strength, the modulus and the strain to failure. If the compressive strength of the FRP is used in design compression tests shall be carried out.

Note: It may not be possible to determine the compressive strength of axial fibres confined between concrete and hoop fibres, by tests on coupons. Manufacturer's data may therefore be accepted until suitable tests are developed.

- ii. FRP bond to concrete: Sample laminates (wet lay-up or pultruded section) shall be installed on specially made concrete test pieces placed alongside the bridge supports being strengthened. The bond strength shall then be determined by tests.

Note: The concrete test piece shall include any intermediate material placed over the bridge support, eg grout filling a gap between the support and a pre-formed FRP laminate.

3.7 Values of material properties used in design shall be the characteristic value (95% exceedance), determined from test data. The characteristic value is the mean minus 1.64 standard deviations of the test results obtained from a sample of at least 10 separate tests for each property to be defined. Tests shall be carried out to UKAS standards, or equivalent, by an independent test house. The test results shall be included in the submission for technical approval.

3.8 Alternatively, the design may be based on material test data provided by a manufacturer. In this case the mean minus two standard deviations (97.3% exceedance) value of test results obtained from a sample of at least 10 separate tests for each property to be defined, shall be used. The test results shall be included in the submission for technical approval.

3.9 The ability of the FRP to resist all aspects of the service environment, eg Road salts, alkali, UV radiation etc. shall be considered. Test data or case studies which include monitoring of service performance shall be provided to demonstrate the ability of the chosen materials to give the required life (normally 30 years).

3.10 Requirements for FRP coupons and samples plus the tests to be carried out shall be specified. Specialist advice shall be sought where necessary.

3.11 Any maintenance requirements shall be clearly specified.

Installation procedure

3.12 A job-specific method statement, covering all aspects of FRP installation, shall be provided by the installer. It shall include contingency plans to deal with foreseeable hazards, including:

- i. Inclement weather.

- ii. Unexpected interruptions to the work or need to clear the site (for example due to traffic accident).
- iii. Plant breakdown at critical times, eg of heaters used to cure the resin.

3.13 The required concrete surface depends to some extent on the FRP materials to be used. The installer shall ensure that the concrete surface is suitable for the material supplied and that the required properties of the finished FRP system are achieved (including the bond to the concrete). The concrete preparation shall be clearly specified by the installer prior to commencement of the work. The specification shall include requirements for:

- i. Cleanliness.
- ii. Dryness of the concrete.
- iii. Freedom from large holes, cracks, changes in profile and sharp protrusions.
- iv. Freedom from contaminates and surface coatings.
- v. Laitance free sound surface concrete.

3.14 Requirements for ensuring the quality of the installation and the properties of the installed materials shall include:

- i. ensuring that installed fibres are straight, eg that there are no kinks and ripples
- ii. ensuring that voids are controlled to an acceptable level
- iii. providing adequate supervision
- iv. providing a clean, dry working environment
- v. temperature control to ensure full cure of the resin
- vi. making and testing sample laminates as described in Clause 3.6.

3.15 The time vs. temperature characteristics shall be given for the resin to be used.

3.16 Pot life and cure times of the resin (eg the time at which the resin will: prevent the wrapping slipping down the column; be waterproof; attain a specified percentage of its design strength) shall be clearly stated in the method statement, with any restrictions on temperature, humidity etc during cure.

3.17 Abnormal loads shall not be permitted on the carriageway supported by the column being strengthened from the time of installation until the resin has cured.

3.18 Where required for UV protection, the surface finish shall be agreed and specified in the contract. The finish shall provide protection for the FRP and an aesthetically acceptable appearance. The service life of the finish shall be at least 15 years.

3.19 The supplier/installer of the FRP wrapping shall supply a manual giving full details of suitable materials and procedures for carrying out repairs to the wrapping, eg following minor collision damage.

3.21 On completion, the work shall be inspected visually and by tapping to identify trapped air, delamination etc.

Note. Several NDE methods are currently at the research stage. They should be used when their reliability has been established.

Quality Control

3.20 Provision shall be made for inspection of the work at each critical stage, including:

- i. Conformity with the method statement.
- ii. The prepared concrete surface.
- iii. The resin, to ensure proper mixing.
- iv. The fibre, to ensure that it is undamaged.
- v. Suppliers' certificates to confirm the type, grade and nominal properties of each material including primer, resin, tack coat, fibre.
- vi. Visual inspection of each layer of FRP before the next layer is applied, to ensure uniformity of fibres and full coverage of resin (wetting), fibre straightness and orientation, and for trapped air.

4. ENQUIRIES

All technical enquiries or comments on this Standard should be sent in writing as appropriate to:

Chief Highway Engineer
The Highways Agency
St Christopher House
Southwark Street
London SE1 0TE

G CLARKE
Chief Highway Engineer

Chief Road Engineer
Scottish Executive Development Department
Victoria Quay
Edinburgh
EH6 6QQ

J HOWISON
Chief Road Engineer

Chief Highway Engineer
Transport Directorate
Welsh Assembly Government
Llywodraeth Cynulliad Cymru
Crown Buildings
Cathays Park
Cardiff CF10 3NQ

J R REES
Chief Highway Engineer
Transport Directorate

Director of Engineering
Department for Regional Development
Roads Service
Clarence Court
10-18 Adelaide Street
Belfast BT2 8GB

G W ALLISTER
Director of Engineering

ANNEX A GUIDANCE ON THE USE OF FRP MATERIALS FOR BRIDGE SUPPORT STRENGTHENING

A.1 MATERIALS

A.1.1 FRP consists of high strength fibres embedded in a resin matrix. The short-term mechanical properties depend mainly on those of the fibres, provided an appropriate resin is used and the composite is correctly designed and installed. When assessing potentially suitable materials, it is important to distinguish the properties of the fibres and those of the FRP composite.

A.1.2 A range of both fibres and resins is currently available and, as with most new technologies, the pace of development is rapid. The fibre types considered suitable for strengthening bridge supports are aramid, carbon and glass. All are elastic to failure in tension, other properties compared to steel, listed here in order of increasing elastic modulus in tension, are generally as follows:

- i. Glass is strong and light, but the elastic modulus in tension is low (about 35% of steel). The fibres may suffer deterioration, so rely on the resin matrix for protection. E-glass is relatively inexpensive compared to aramid and carbon, but it is less durable. Alkali resistant (AR) glass is more durable but also more expensive. Strain to failure is around 4.5%. Resistance to impact and abrasion is good and glass fibre is used in some applications as a protective layer for carbon fibre components, eg small pressure vessels.
- ii. Aramid is strong, light, durable if protected from uv radiation and robust (uv is generally only a problem during transport and storage). Moisture take-up may result in some degradation of mechanical properties. Its elastic modulus in tension is about half that of steel, strain to failure is 2.3%. Due to its failure mechanism, aramid fibres are used in applications requiring resistance to impact and abrasion, eg protective clothing. Aramid is more expensive than glass, but likely to be less expensive than carbon.
- iii. Carbon is strong, light, durable and expensive. The grades most likely to be used in civil engineering have an elastic modulus in tension about the same as steel and strain to failure of around 1.7%. A range of properties can be

obtained, but the higher grades may be much more expensive. High modulus carbon is not suitable for column wrapping for impact due to its low strain to failure, generally <1%. Carbon fibre is said to have low impact strength and a protective layer of glass fibre has been used in other applications.

A.1.3 FRP composites installed by the 'wet lay-up' process are likely to contain around 40-45% fibres. Pre-impregnated fibres may have up to 65% fibre content.

A.1.4 The fibre properties are directional; the most efficient composite has all the fibres aligned in the direction of the applied stress (unidirectional fibres). The strength and stiffness are significantly reduced if the fibres are not so aligned.

A.1.5 Fibres can be woven in a similar manner to other textiles with varying percentages of fibre placed at right angles (or at other angles). The properties of the resulting fabric in a given direction are also affected by the weave (the fibres are not initially straight). Unidirectional (UD) fabric is likely to be most efficient in terms of use of material. In this case all the structurally acting fibres are in one direction, a small percentage of fibre (around 8%) is provided at right angles to hold the fabric together. However, overall cost-effectiveness depends on many other factors, eg installation time.

A.1.6 Of the currently available resins which are potentially suitable for use with concrete, polyester has good mechanical properties and is relatively cheap, but there is some doubt about its long-term durability. Epoxy resins also have good mechanical properties and, if correctly formulated they are durable in a concrete environment; but they are more expensive and are damaged by long-term exposure to UV radiation. Vinyl esters combine some of the properties of each. In the current state of knowledge, it is considered that only epoxy resins can provide an acceptably low risk of premature failure. Even so, 'epoxy' is a family of resins, not all would be durable and careful formulation is required.

A.1.7 There are many standards and test procedures to establish the properties of FRP materials, but none specifically for use in civil engineering construction. There is considerable variation and some ambiguity in the presentation of the properties of FRP products. A number of factors contribute to this:

- The properties of the installed composite depend on the design (the way the fibres are used, eg their orientation) and on the standard of installation, as well as the material properties of the fibre and resin.
- At present there appears to be more variability in the properties of some materials; hence the margin between the mean property and the design value must be carefully considered. Manufacturers may present design data based on different statistical interpretations of the test data.

A.2 PARTIAL SAFETY FACTORS

A.2.1 There are currently insufficient data to provide a statistical basis for partial factors for FRP materials. The values of γ_m given in this Standard are based on available data, comparison with steel and concrete, engineering judgement and consistency with other standards; they may be revised as new information becomes available. A key requirement is to define what is covered by each partial safety factor. Tensile test data is available for most fibres. Hence the starting point is the characteristic value, eg a value which should be exceeded by 95% of samples. Partial safety factors are applied to this value.

A.2.2 Fibres, fabric and tow sheets are factory produced and subject to quality control. Fibre manufacturers test their products and can generally supply material property data. Their advice on properties to be used for design is restricted to ultimate strength, and the suggested design values vary down to 50% of that obtained from tests. The requirements of this Standard may be satisfied by obtaining tensile test data from the manufacturer and taking the mean minus two standard deviations value of strength and strain to failure as design values.

A.2.3 The composite laminate may be factory produced, eg pultruded plate, or made on site by wet lay-up. It may be expected that the amount and distribution of resin in a factory-produced laminate would be more closely controlled and tensile test data should be available. However, the laminate has to be bonded to the concrete on site; bonding to a fully

polymerised resin is an additional operation compared to wet lay-up and carries the same uncertainty as any adhesive bond.

A.2.4 The wet lay-up process may be compared to cast in situ concrete. The constituent materials are subject to quality assurance, but the properties of the installed material also depend on the mixing and placing procedures.

A.2.5 The factors given in this Standard are intended to cover uncertainties in both materials and installation. As the FRP is not intended to carry any long-term load, only short term properties are relevant. However, durability does need to be considered. Some of the factors which could affect the service performance of FRP strengthening on a bridge support and their possible causes are:

Systems based on wet lay-up installation of fibres, fabric or tow sheets:

- i. Risk of some fibres having properties outside specification.
 - Production fault.
 - Damage in storage or transit.
 - Damage during installation.
- ii. Risk of some resin being outside specification.
 - Production fault.
 - Incorrect storage.
 - Incorrect mixing.
 - Environment during installation, eg temperature, humidity.
- iii. Installation procedure (wet lay-up).
 - Incomplete wetting of fibres.
 - Non-uniform distribution of resin.
 - Excessive voids in resin.
 - Incorrect alignment of fibres.
 - Fibres not straight.
 - Incorrect placing of fibres.
 - Unauthorised/incorrect joints.

Systems based on laminates (eg pultruded):

iv. Laminates.

Production faults - materials or process parameters.
Damage in storage or transit.
Damage during installation.

v. Bond to concrete (eg local).

Adhesive bond of pultruded laminate to concrete.

All systems:

vi. Bond to concrete (eg Local)

Poor surface concrete.
Uneven concrete surface.
Primer/putty - faulty/damaged material, faulty application

vii. Incompatibility between materials.

(Concrete/primer/putty/tack coat/resin/fibre or tack coat/adhesive/laminate)

viii. Thermal effects.

Strain/micro cracking due to differential expansion.
Risk of exceeding the glass transition temperature of the resin.

ix. Long term effects

“Corrosion” of E-glass fibres.
Chemical attack of glass or aramid fibre.
Chemical attack of resin.
Corrosion of steel reinforcement due to trapped chlorides.

Note. Stress rupture and fatigue are not relevant;

x. Inaccuracies in modelling the structural behaviour of the FRP.

xi. Inaccuracies in modelling the behaviour of confined concrete.

ANNEX B DESIGN CHARTS FOR STRENGTHENING OF CIRCULAR COLUMNS

B.1 DESIGN CHARTS

Introduction

B.1.1 The design charts included in this annex may be used to determine the thickness of axial fibres required to strengthen circular concrete columns in flexure. The design charts are based on the design approach set out in Clauses 2.17 and 2.18 and are valid for all fibre types.

B.1.2 To limit the total number of design charts required some conservative approximations have been made. In particular, any contribution to the flexural strength of the column made by the FRP in compression is neglected.

B.1.3 Design charts have been developed for different values of ω , termed the reinforcement capacity ratio, given by:

$$\omega = \frac{A_s (f_y / \gamma_{ms})}{\pi R_c^2 (f_{cw} / \gamma_{mc})} \quad (\text{B.1})$$

where A_s is the total area of longitudinal steel reinforcement in the section. Linear interpolation of the thickness of axial fibres may be used for intermediate values of ω .

Different charts are applicable to high yield and mild steel reinforcement and to confined and unconfined concrete. For the purposes of the design charts the terms high yield steel, mild steel, confined concrete and unconfined concrete are used to denote the following ranges of material properties:

- (i) High Yield Steel: $400 < \sigma_{ys} < 460$
- (ii) Mild Steel: $200 < \sigma_{ys} < 250$
- (iii) Confined Concrete: $\epsilon_{cp} = 0.01$
- (iv) Unconfined Concrete: $0.0035 \leq \epsilon_{cp} < 0.01$

In some instances one chart may be applicable to, for example, both confined and unconfined concrete.

The charts should not be used when the steel yield stress exceeds the maximum in the range; they may however be used conservatively for yield stresses below the minimum in the range. The charts are summarised in Table B.1.

Steel Type	Concrete	ω								
		0.02	0.06	0.1	0.15	0.2	0.25	0.3	0.35	0.4
High Yield	Confined	1	2	4	6	9	13	17		
	Unconfined	1	2	4	7	10	14	18	19	20
Mild	Confined	1	3	5	8	11	15			
	Unconfined	1	3	5	8	12	16			

Table B.1: Chart Numbers and Parameters

B.1.4 The design charts may also be used to establish whether a design uses the FRP efficiently and can assist in the selection of fibre type. Further guidance in these areas is provided in [1], where the theoretical background to the charts is described.

B.1.5 The conservatism in the thickness of axial fibres determined using the design charts increases as:

- (i) σ_{ys} decreases from the maximum in the range specified in Clause B.1.3,
- (ii) ϵ_{cp} increases from the minimum in the range specified in Clause B.1.3,
- (i) $\frac{-\epsilon_{wt}}{\epsilon_{cp}}$ decreases (this parameter is determined using the charts),
- (ii) ω increases.

The conservatism may become significant when $\frac{-\epsilon_{wt}}{\epsilon_{cp}}$ decreases below 0.67.

B.1.6 The method for using the design charts is summarised in the flow chart in Figure B.1 and makes use of the following formulae:

$$N_{uw} = N - (N_{us} + N_{uc}) \quad (B.2)$$

$$t_l = \frac{-k_l N_{uw}}{R_c \epsilon_{cp} (E_{wt} / \gamma_{mwE})} \quad (B.3)$$

A Design Example is included in Annex B.2.

[1] Denton, S.R. and Christie, T.J.C., "Design Charts for Strengthening Circular Concrete Columns using FRP", in preparation.

B.2 DESIGN EXAMPLE

Design Parameters

A circular column has the following properties:

$$R_c = 0.4\text{m} \quad f_{cu} = 40 \text{ MPa}$$

It is reinforced with 16 high tensile bars with 20mm diameter and a characteristic yield stress equal to 460 MPa. The effective radius to the steel reinforcement is 0.36m. The column is provided with circumferential (hoop) FRP in accordance with Clause 2.12 and has adequate shear capacity.

The column is to be strengthened with an Aramid fibre with the following properties:

$$E_{wt} = 100 \text{ GPa} \quad \epsilon_{wtm} = -0.023$$

The coexistent ultimate axial force and bending moment applied to the section of the column under consideration are:

$$N = 2250 \text{ kN} \quad M = 1650 \text{ kNm}$$

The circumferential FRP applied to the column is in accordance with Clause 2.12, therefore enhanced confined concrete properties may be used, given by:

$$f_{cw} = 1.5 \times 40 = 60 \text{ MPa}$$

$$\epsilon_{cm} = 0.01$$

Application of Design Chart Method

Relevant lines are plotted on the design chart in Figure B.2. The procedure set out in the flow chart in Figure B.1 is followed.

$\epsilon_{cp} = \epsilon_{cm}$, therefore

$$\epsilon_{cp} = 0.01$$

From Equation B.1, the reinforcement capacity ratio is given by:

$$\omega = (16 \times \pi \times 20^2/4 \times 460/1.15) / (\pi \times 400^2 \times 60/1.5) = 0.1$$

Therefore, from Table B.1, the relevant design chart is Chart 4.

Effective radius of steel divided by column radius is given by:

$$R_s / R_c = 360/400 = 0.9$$

The Horizontal Strain Capacity line is plotted on the middle section of the design chart (see Figure B.2) at:

$$-\epsilon_{wtm} / (\gamma_{mwe} \epsilon_{cp}) = 0.023 / (1.2 \times 0.01) = 1.92$$

The coordinates of Point A are:

$$\begin{aligned} & \{N / R_c^2 (f_{cw} / \gamma_{mc}), M / R_c^3 (f_{cw} / \gamma_{mc})\} \\ &= \{2250 / (0.4^2 \times 60/1.5 \times 1000), 1650 / (0.4^3 \times 60/1.5 \times 1000)\} \\ &= \{0.352, 0.645\} \end{aligned}$$

This point is plotted on Figure B.2 as Point A. A line is plotted parallel to the nearest dashed generator to intersect the $R_s/R_c=0.9$ curve at Point B. A vertical line is plotted through Point B to intersect the $R_s/R_c=0.9$ curves at Points C and D on the middle and bottom sections of the chart respectively.

From the middle section of the chart it can be seen that Point C lies below the Strain Capacity line and therefore the strain capacity of the FRP is not exceeded.

From the design chart the coordinates of Point D are given by:

$$(N_{us} + N_{uc}) / R_c^2 (f_{cw} / \gamma_{mc}) = 0.54 \quad k_1 = 0.24$$

Therefore,

$$N_{us} + N_{uc} = 0.54 \times 0.4^2 \times 60/1.5 \times 1000 = 3456 \text{ kN}$$

Applying Equation B.2,

$$N_{uw} = 2250 - 3456 = -1206 \text{ kN}$$

Applying Equation B.3,

$$t_1 = (-0.24 \times -1206) / (0.4 \times 0.01 \times 100 / 1.2 \times 1000) = 0.87 \text{ mm}$$

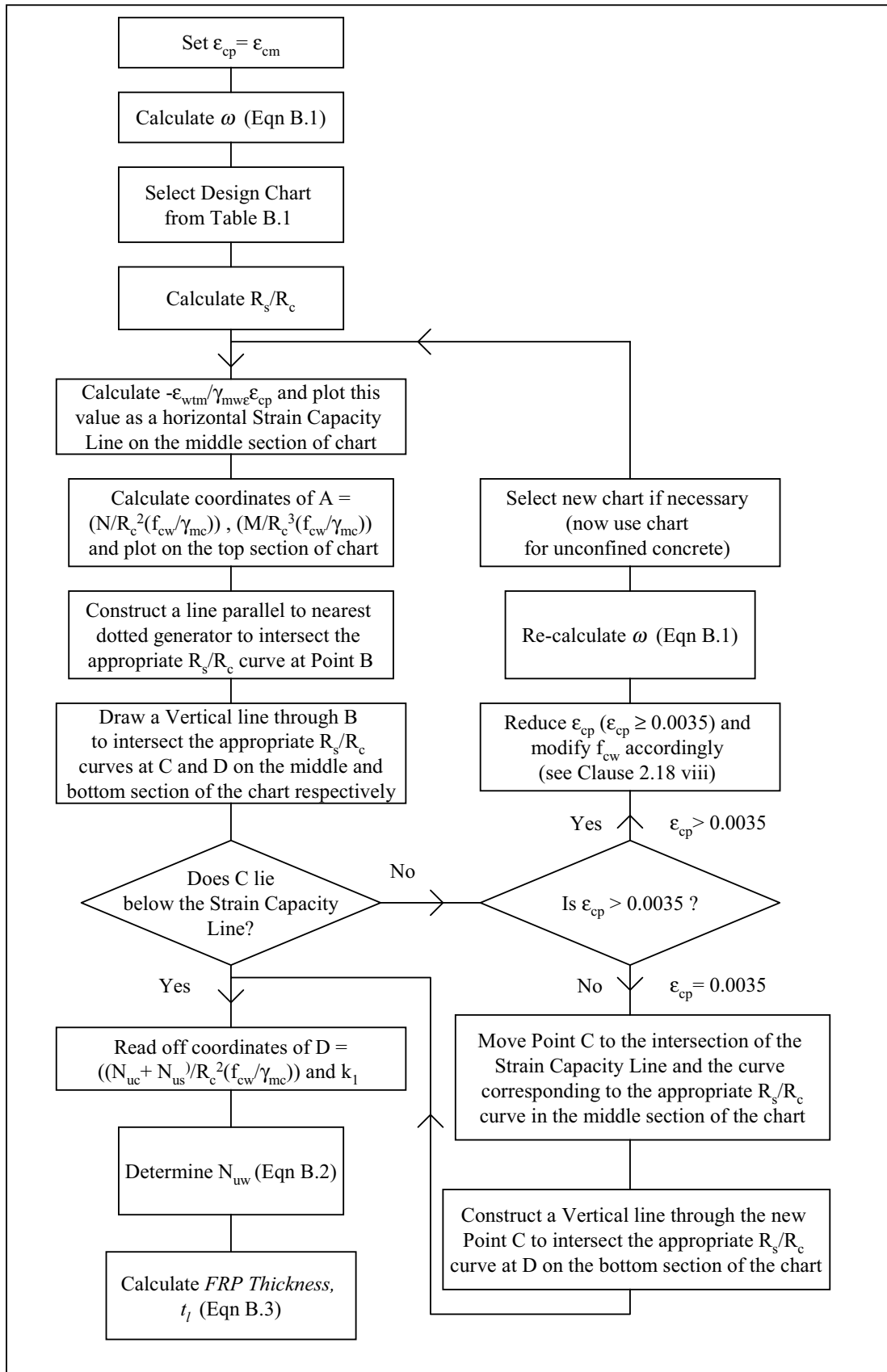


Figure B.1: Application of Design Charts

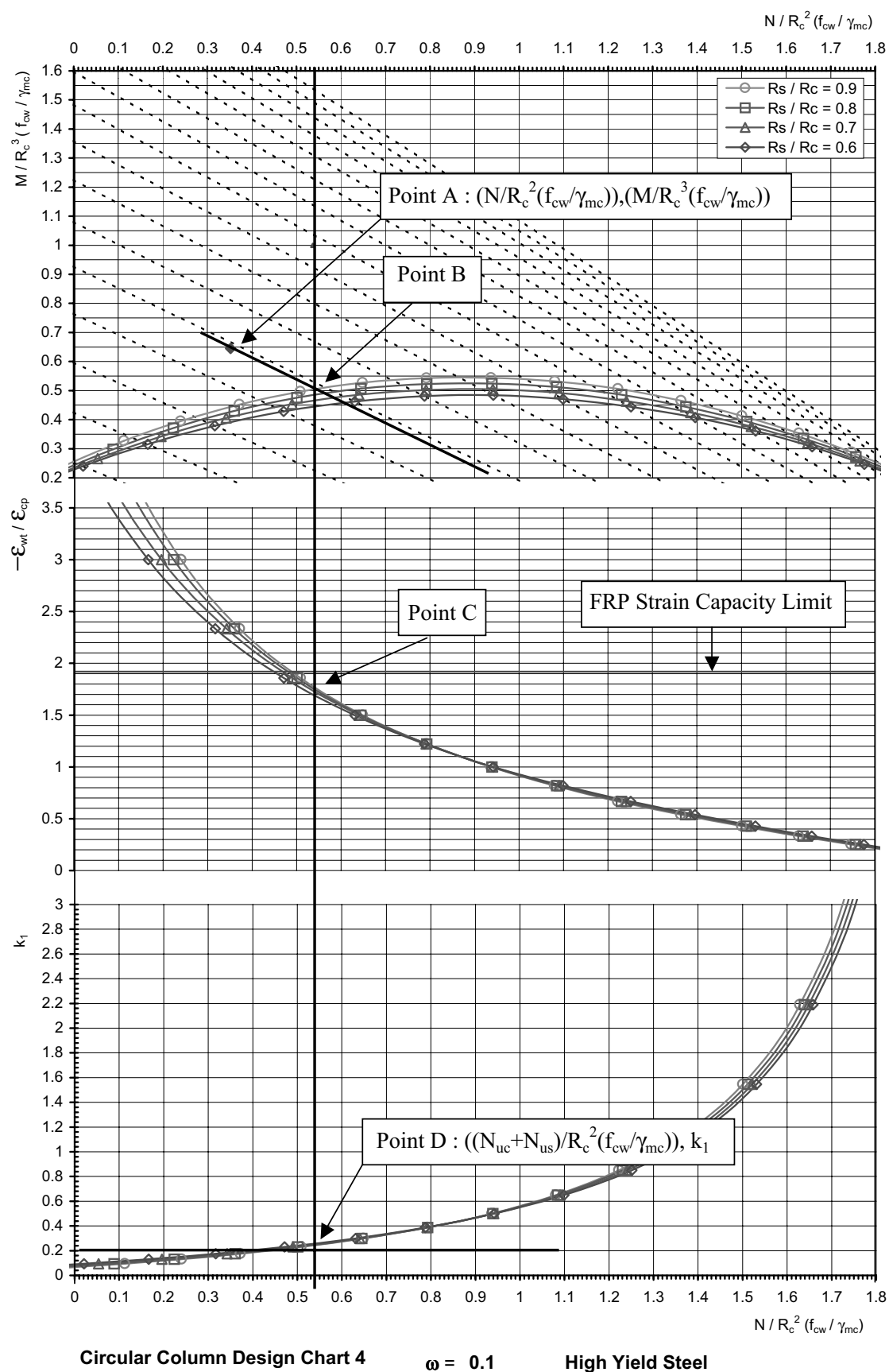
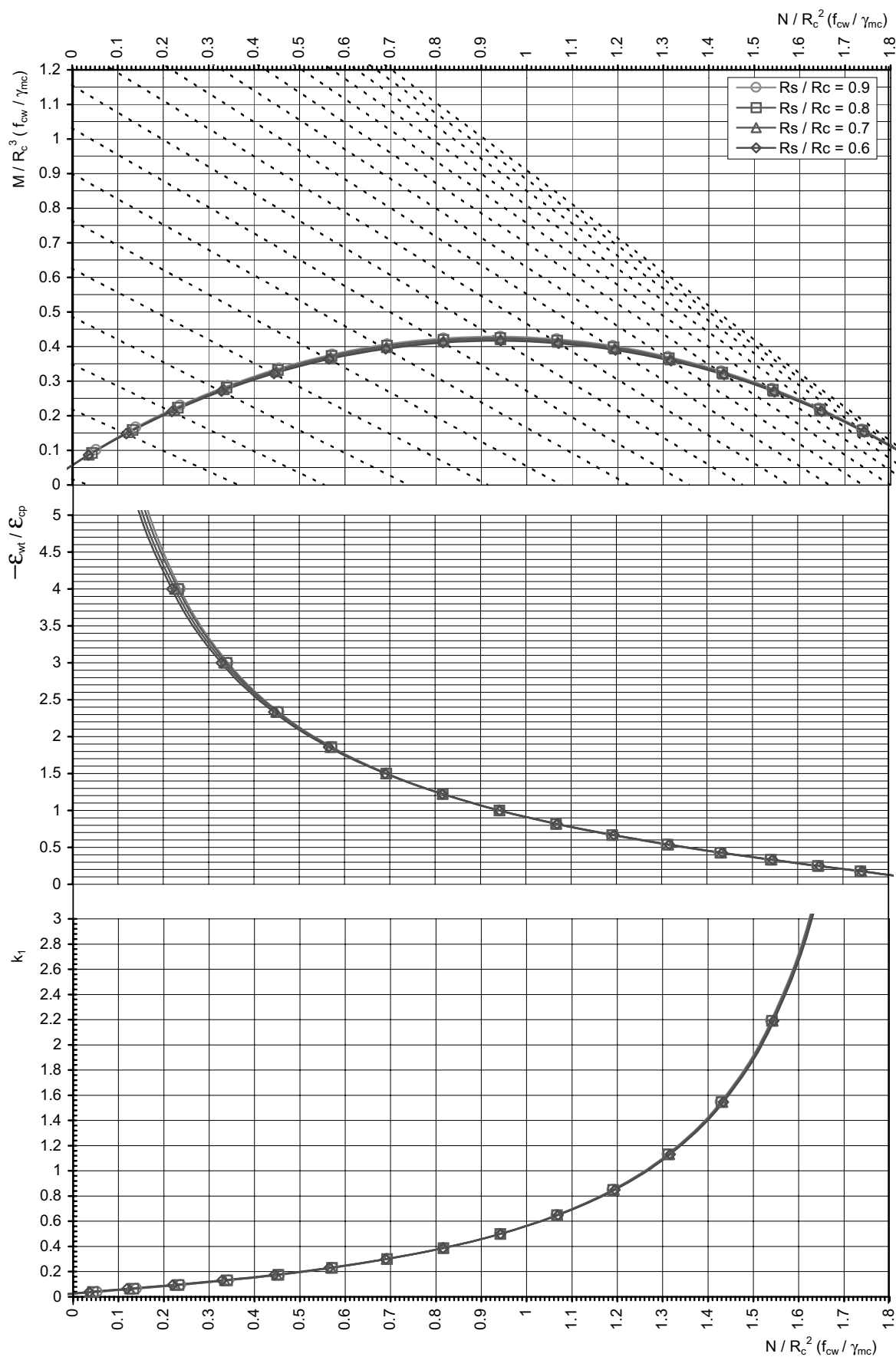
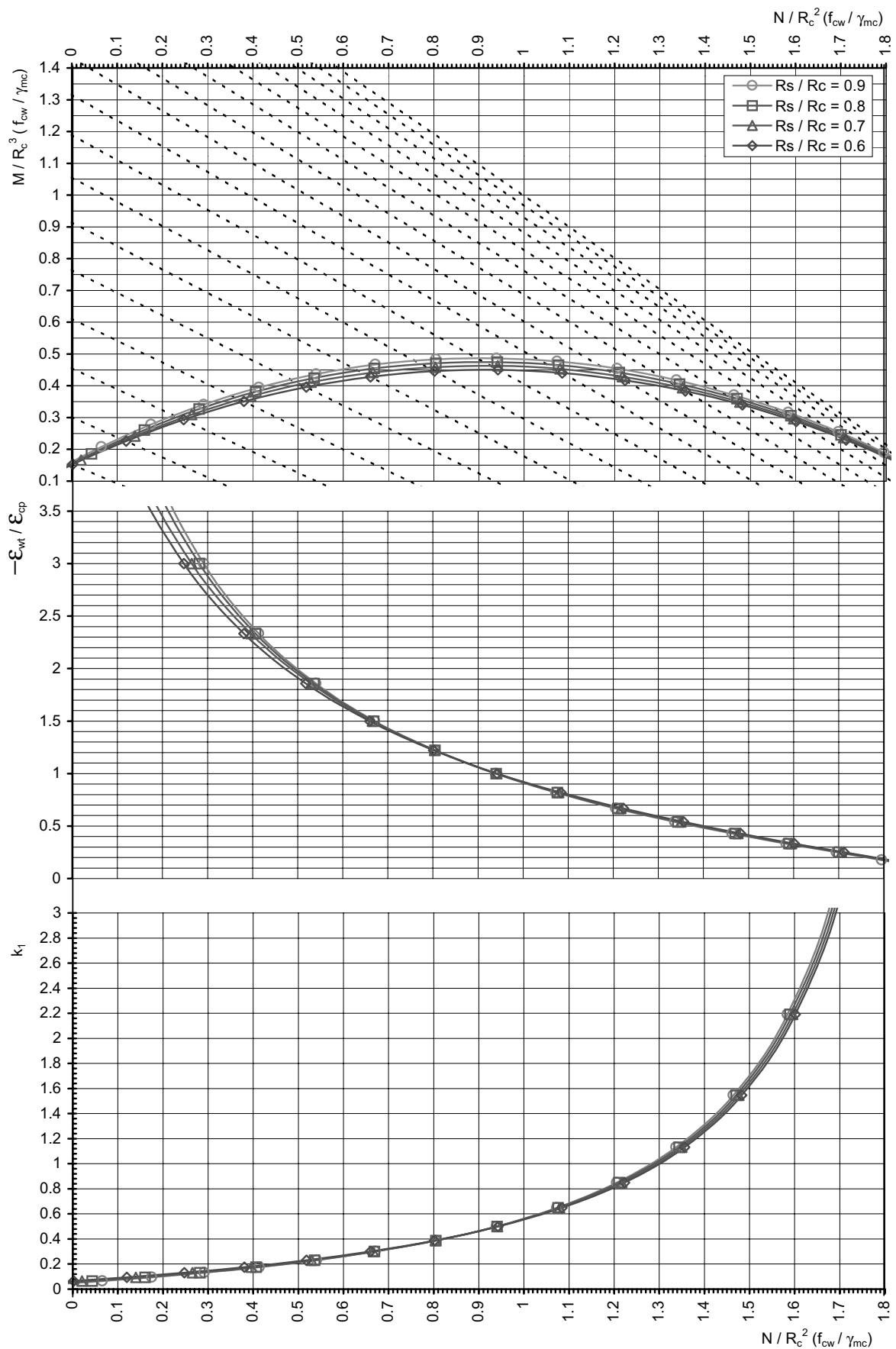


Figure B.2: Example



Circular Column Design Chart 1

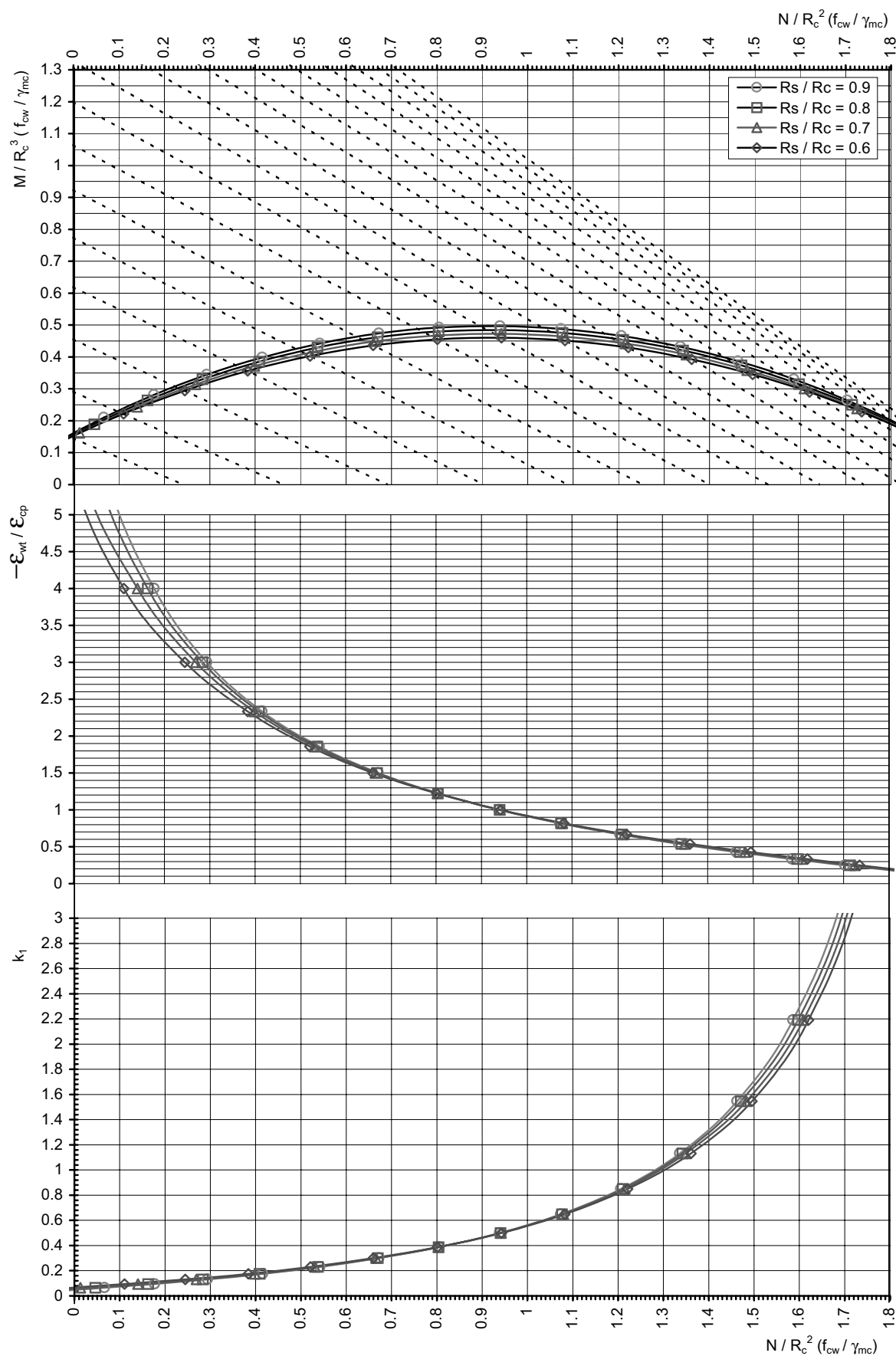
$\omega = 0.02$



Circular Column Design Chart 2

$\omega = 0.06$

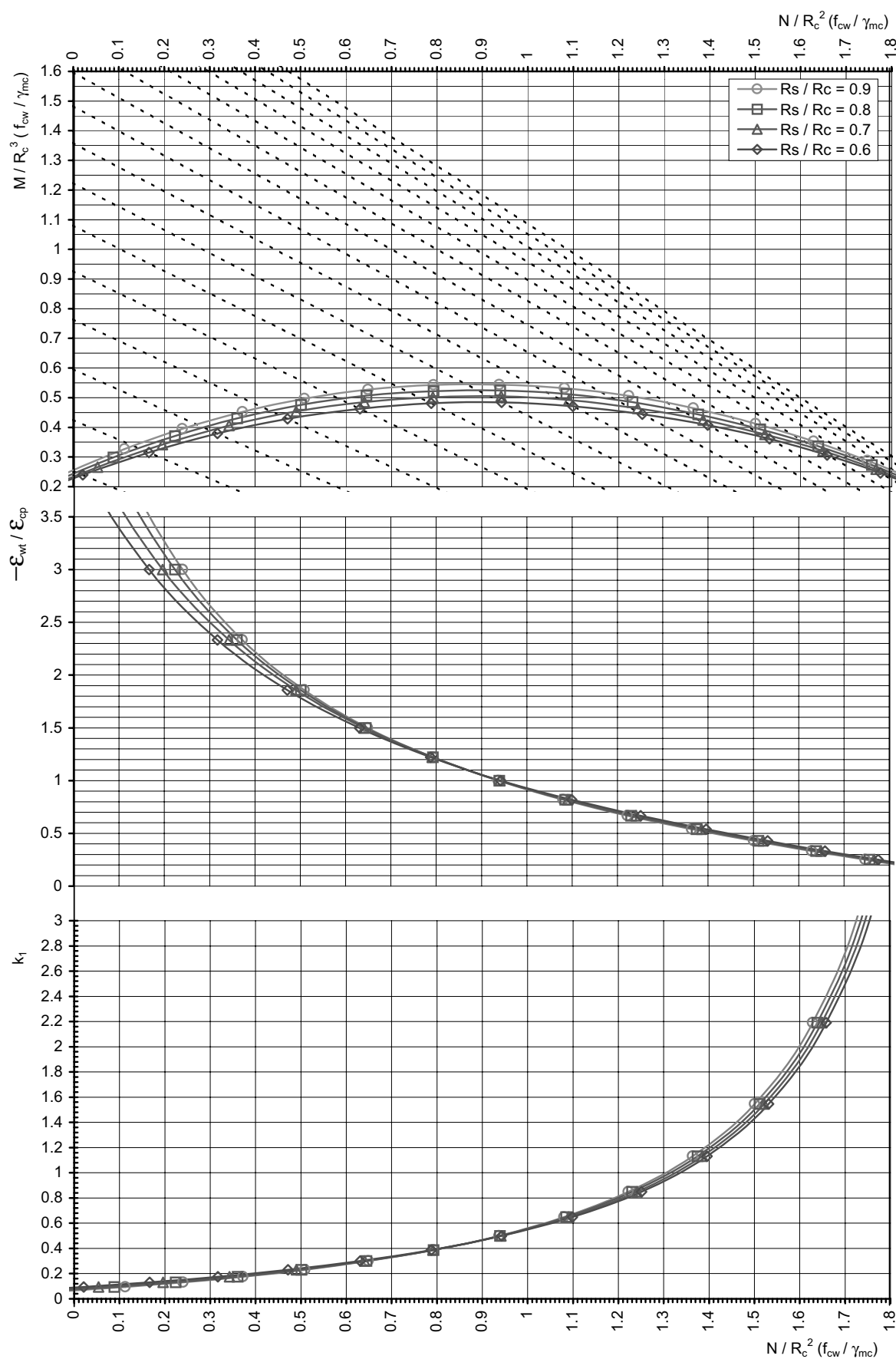
High Yield Steel



Circular Column Design Chart 3

$\omega = 0.06$

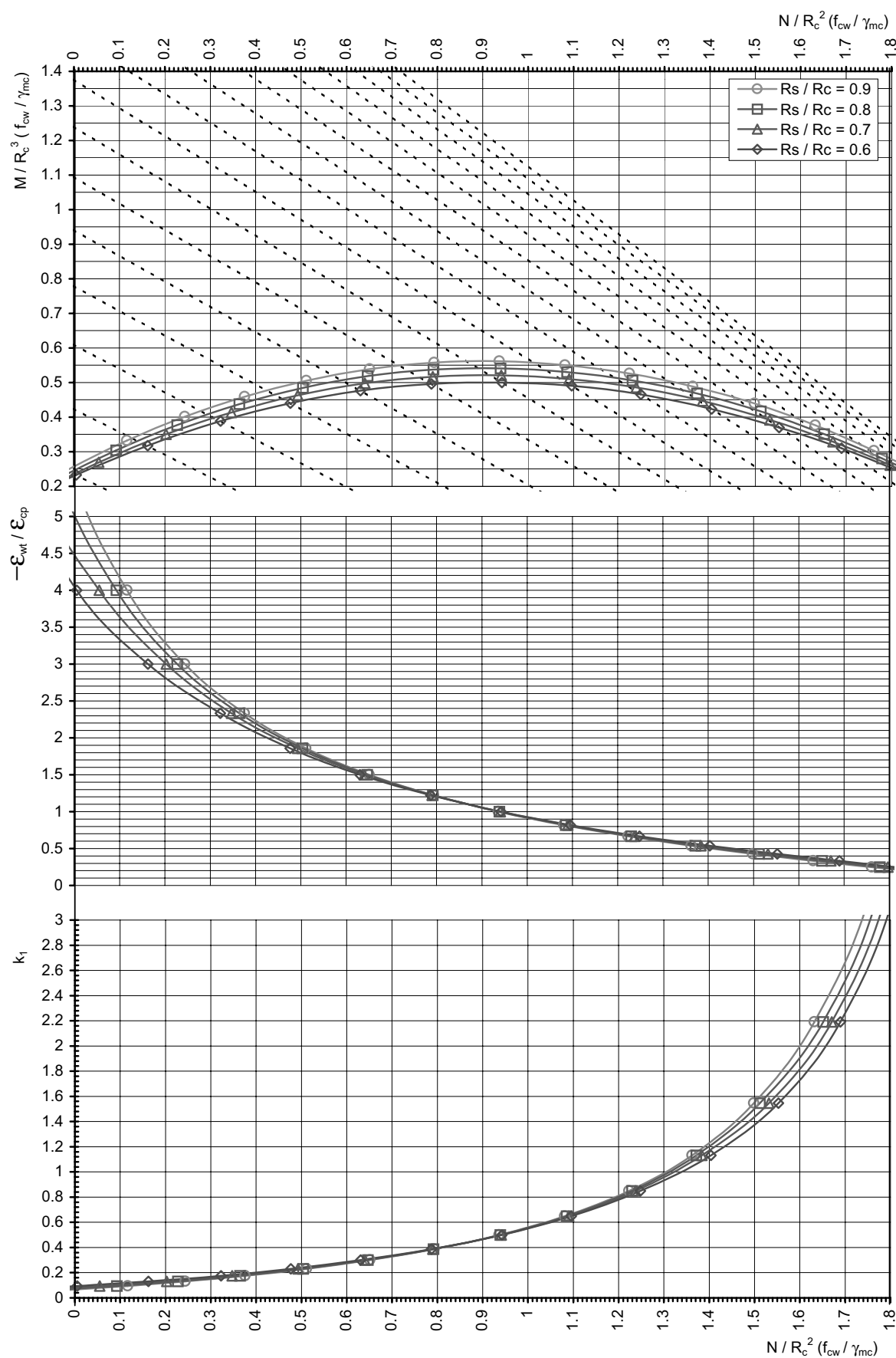
Mild Steel



Circular Column Design Chart 4

$\omega = 0.1$

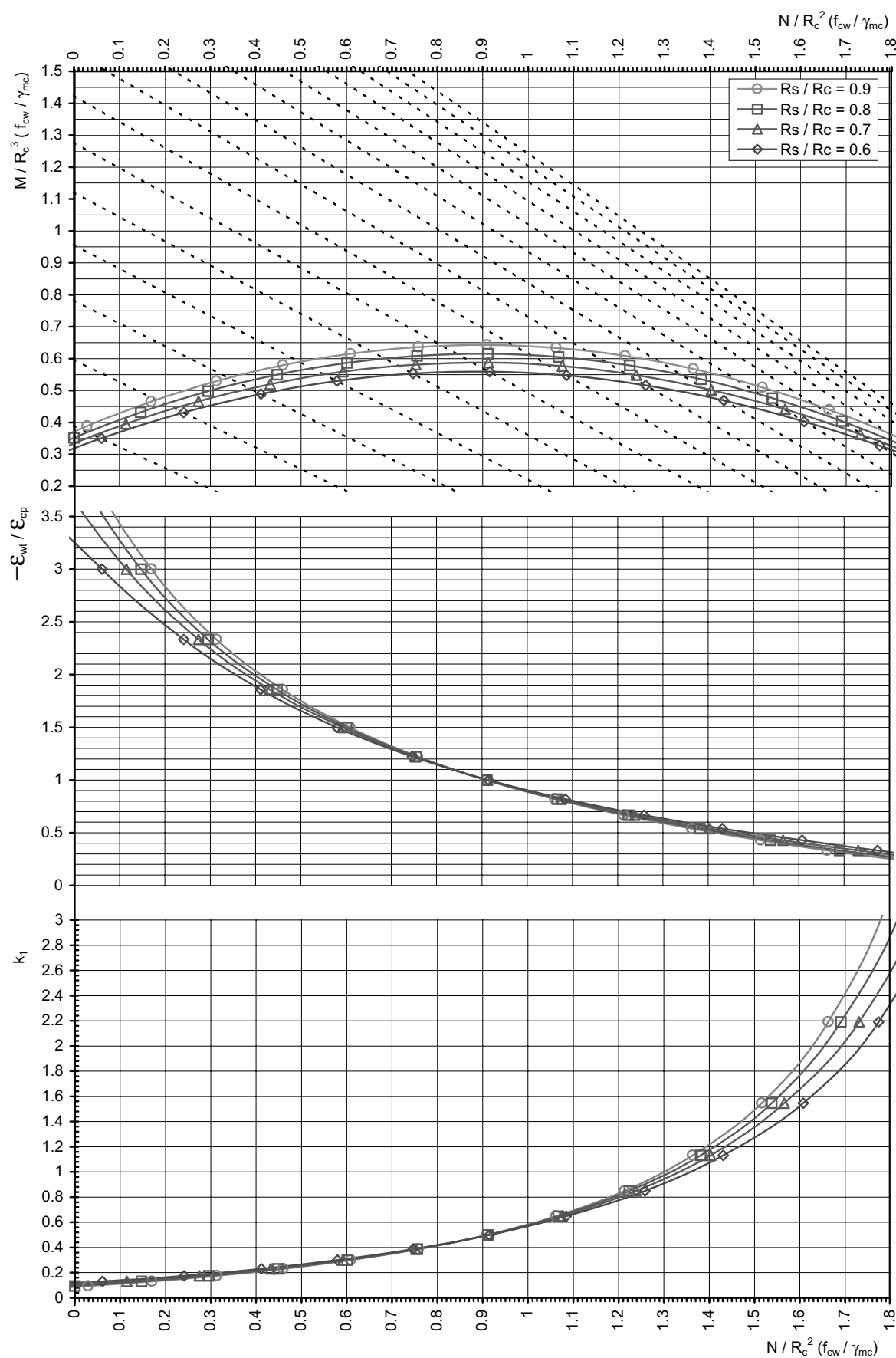
High Yield Steel



Circular Column Design Chart 5

$\omega = 0.1$

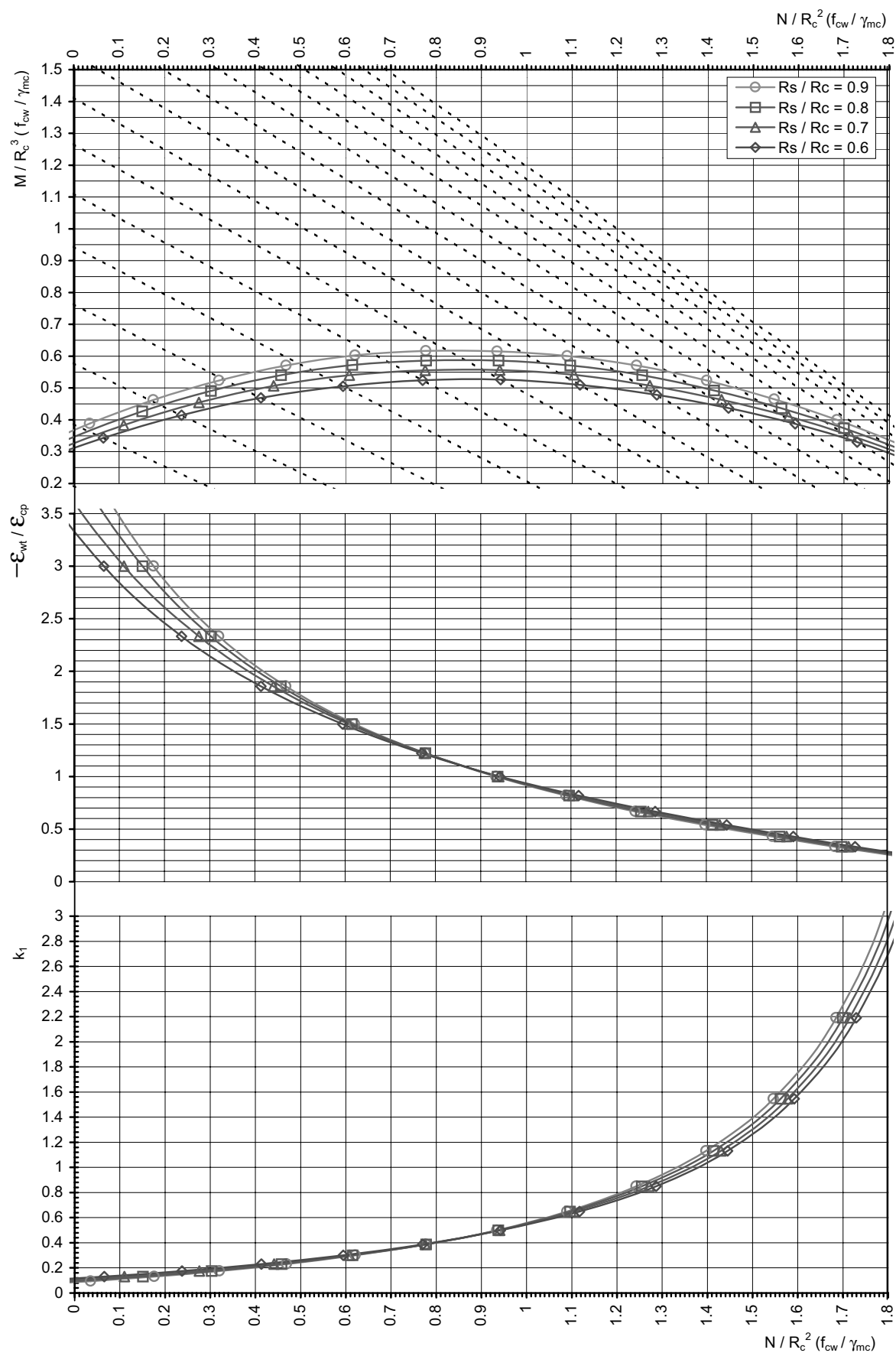
Mild Steel



Circular Column Design Chart 6

$\omega = 0.15$

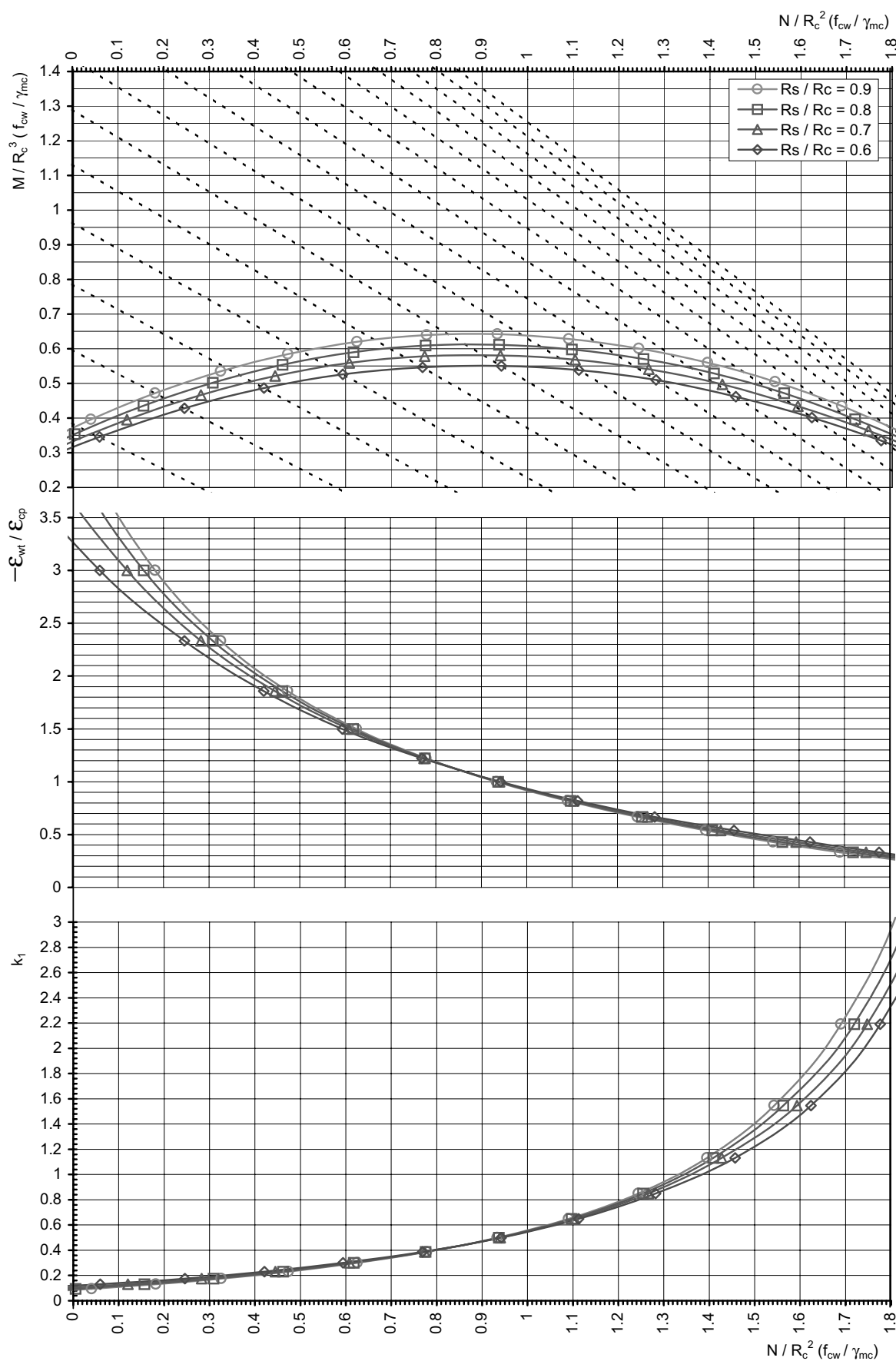
High Yield Steel, Confined Concrete



Circular Column Design Chart 7

$\omega = 0.15$

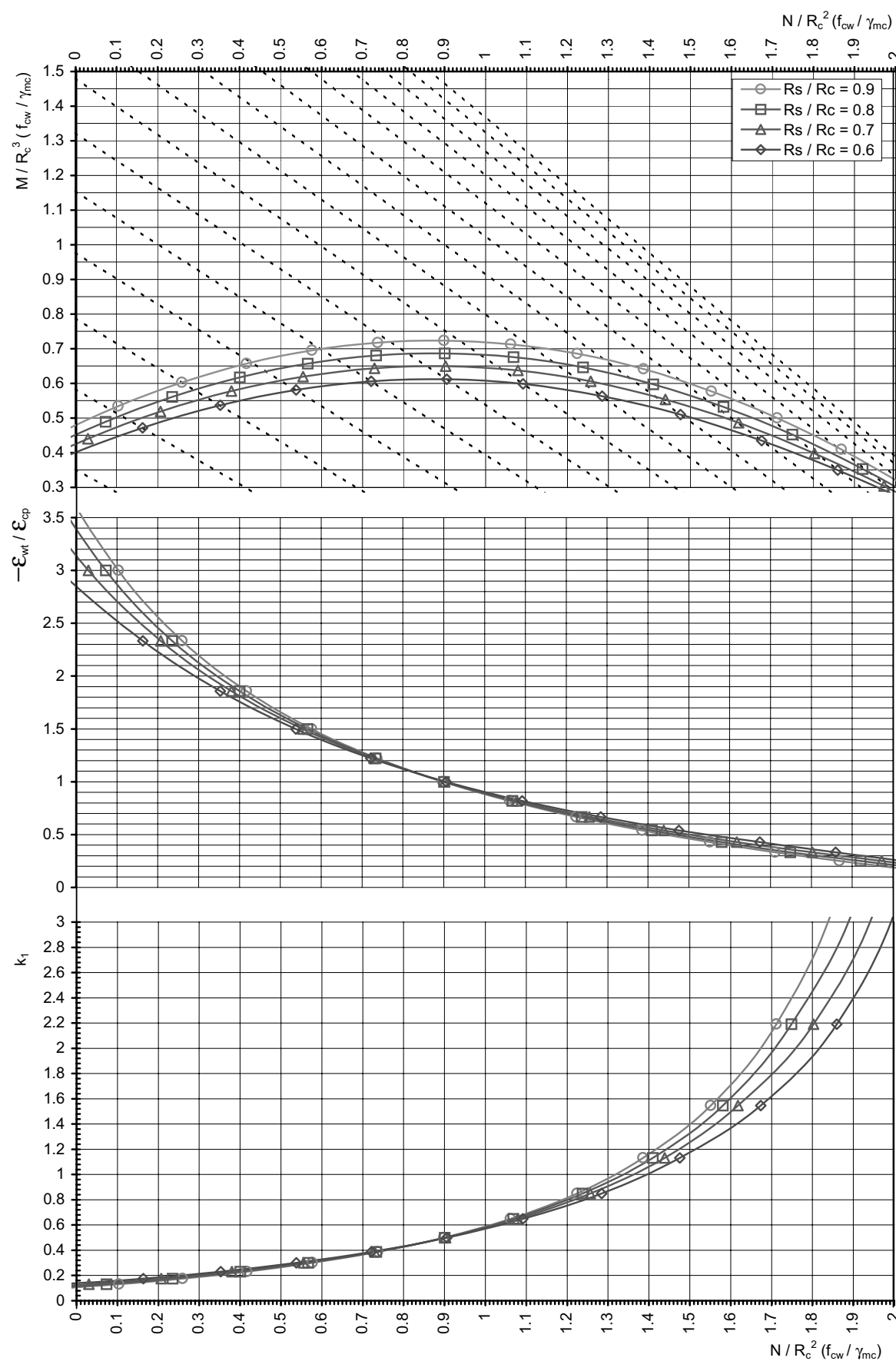
High Yield Steel, Unconfined Concrete



Circular Column Design Chart 8

$\omega = 0.15$

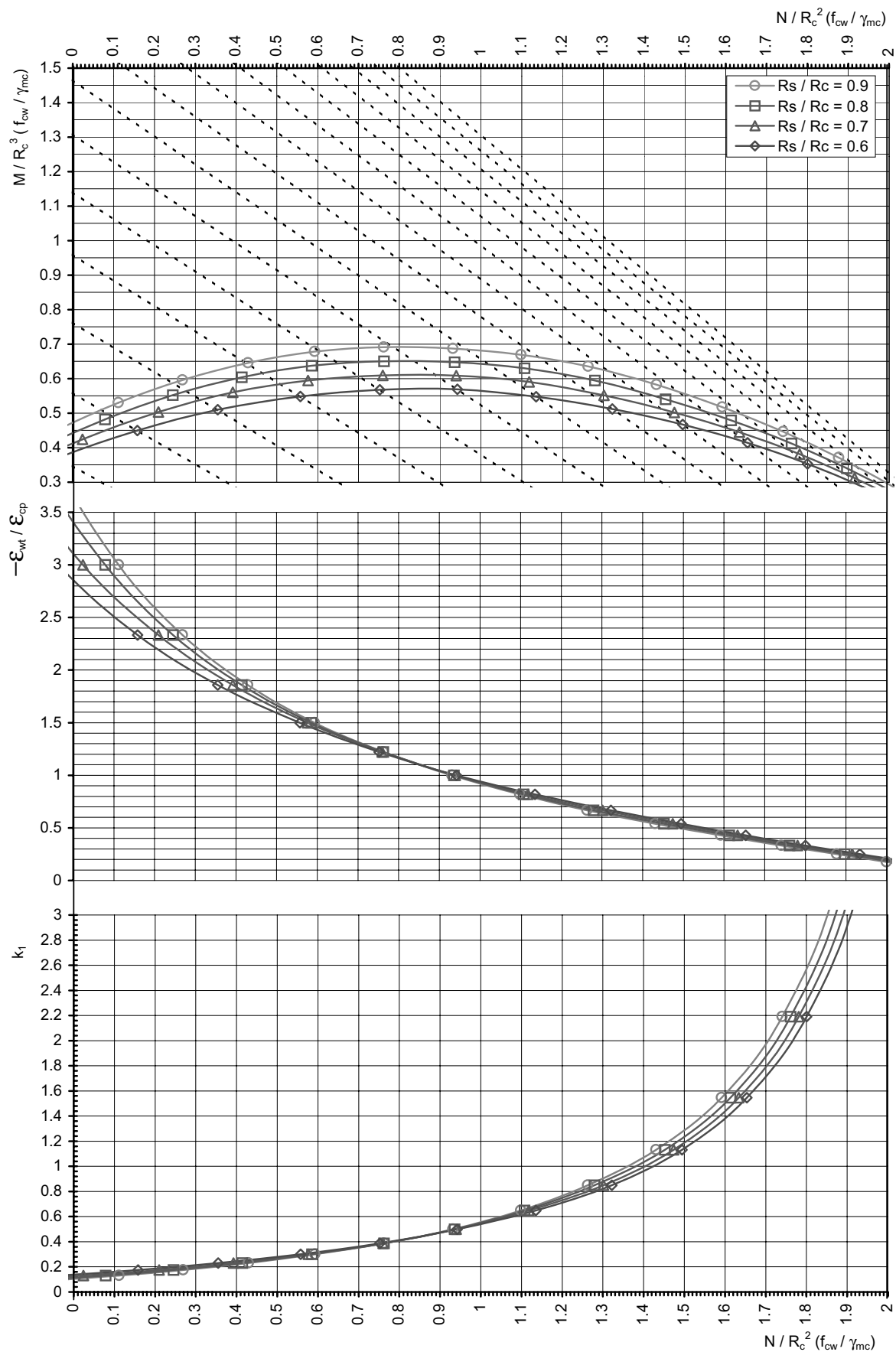
Mild Steel



Circular Column Design Chart 9

$\omega = 0.2$

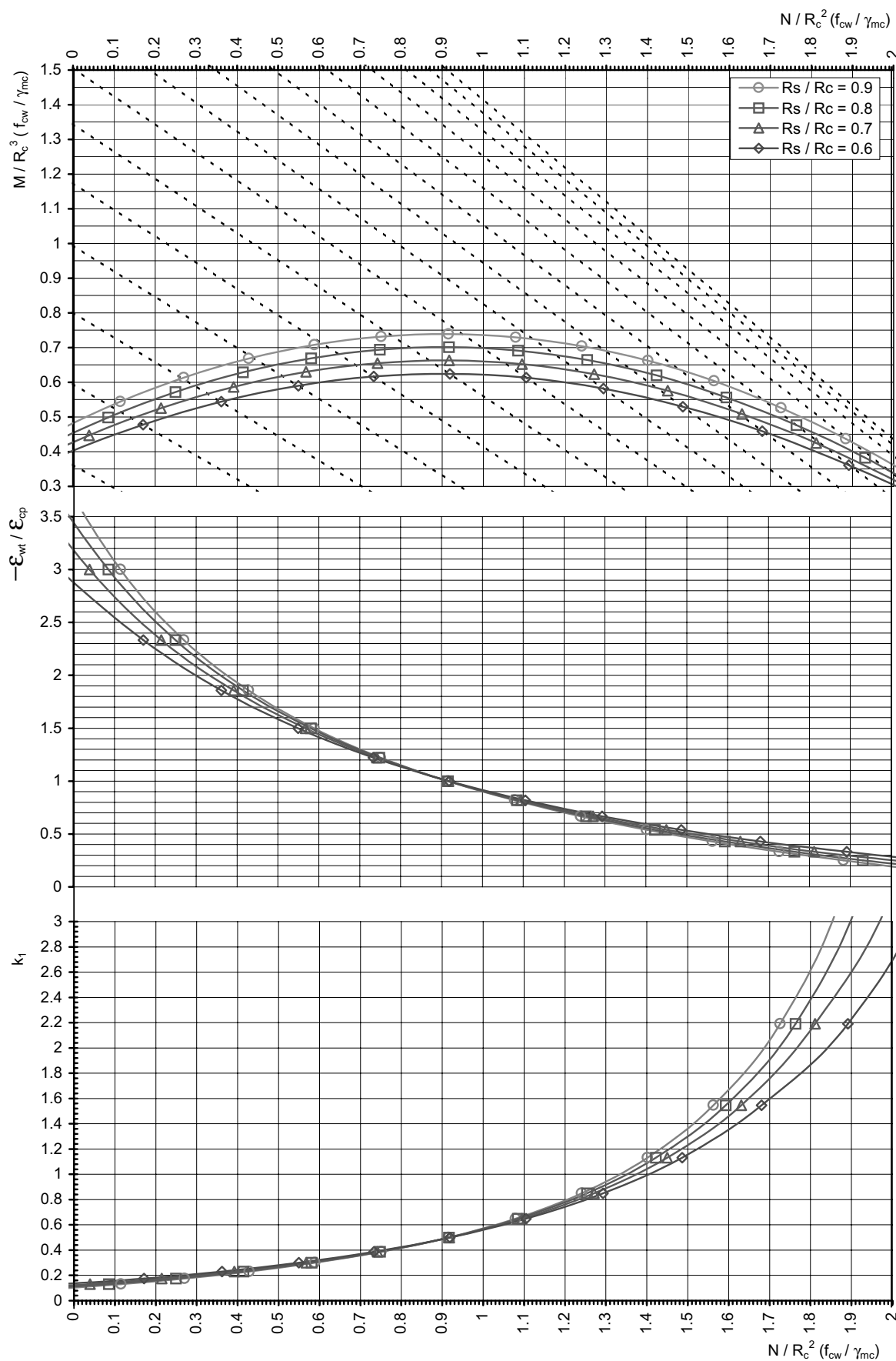
High Yield Steel, Confined Concrete



Circular Column Design Chart 10

$\omega = 0.2$

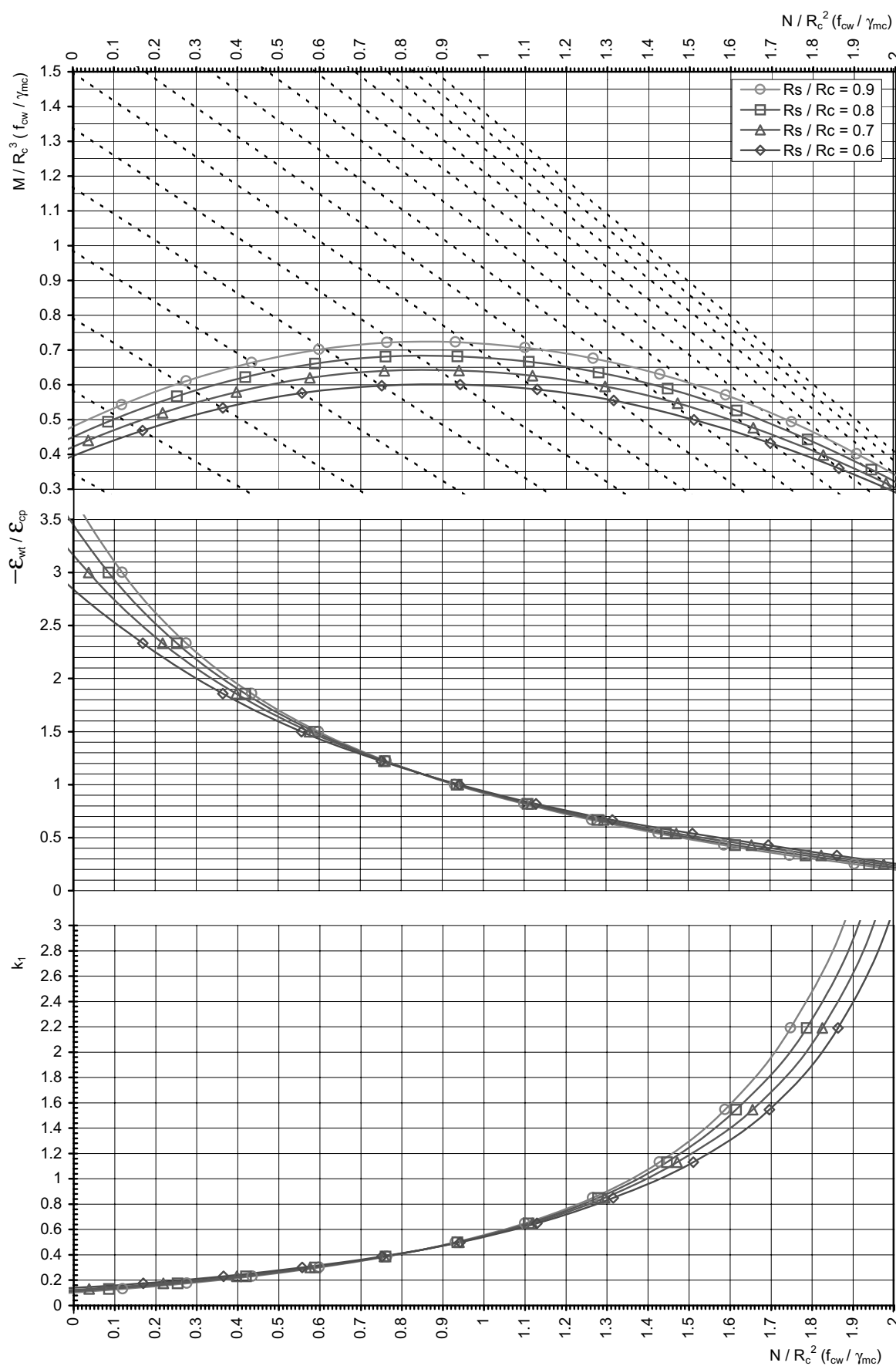
High Yield Steel, Unconfined Concrete



Circular Column Design Chart 11

$\omega = 0.2$

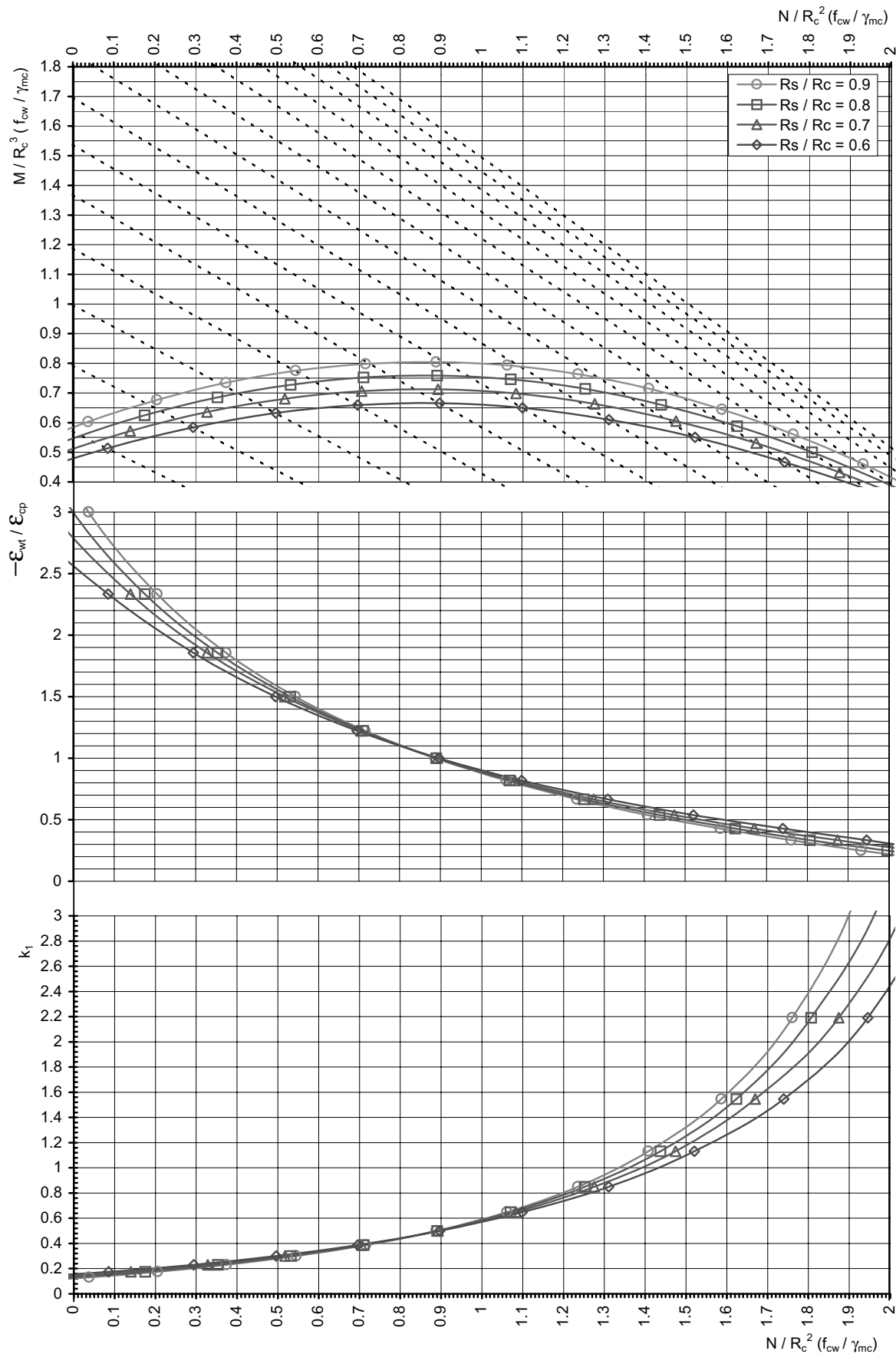
Mild Steel, Confined Concrete



Circular Column Design Chart 12

$\omega = 0.2$

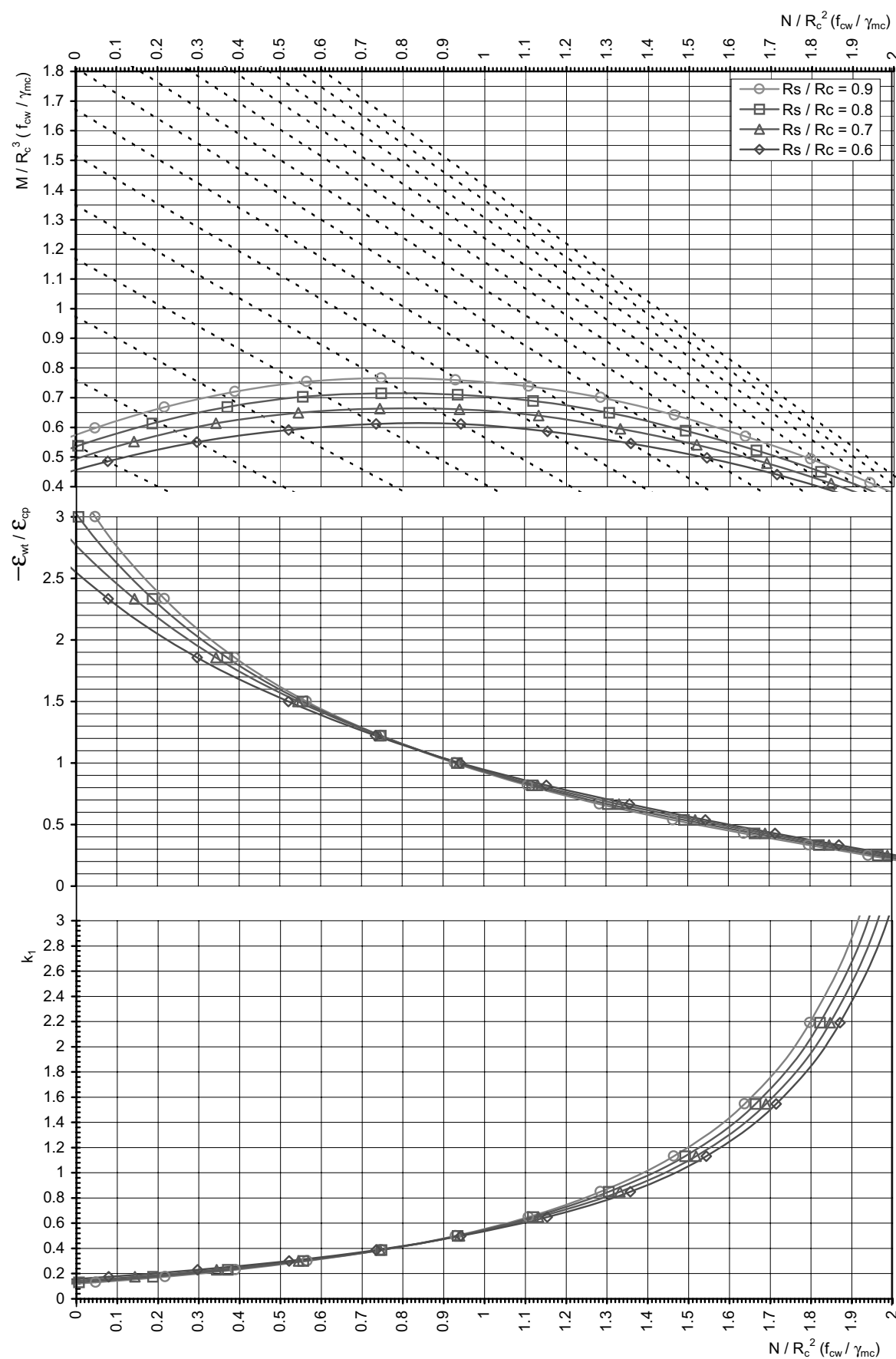
Mild Steel, Unconfined Concrete



Circular Column Design Chart 13

$\omega = 0.25$

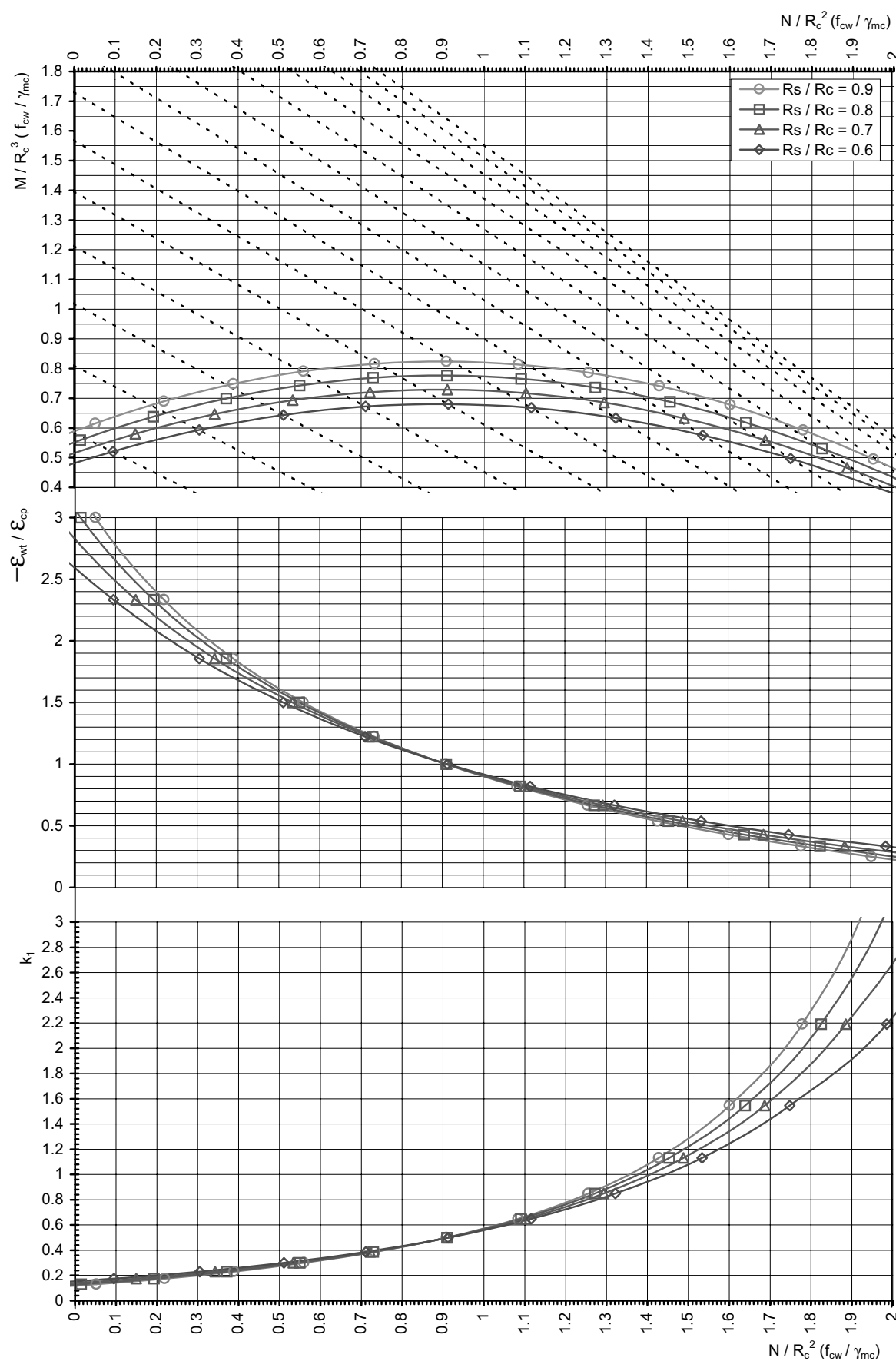
High Yield Steel, Confined Concrete



Circular Column Design Chart 14

$\omega = 0.25$

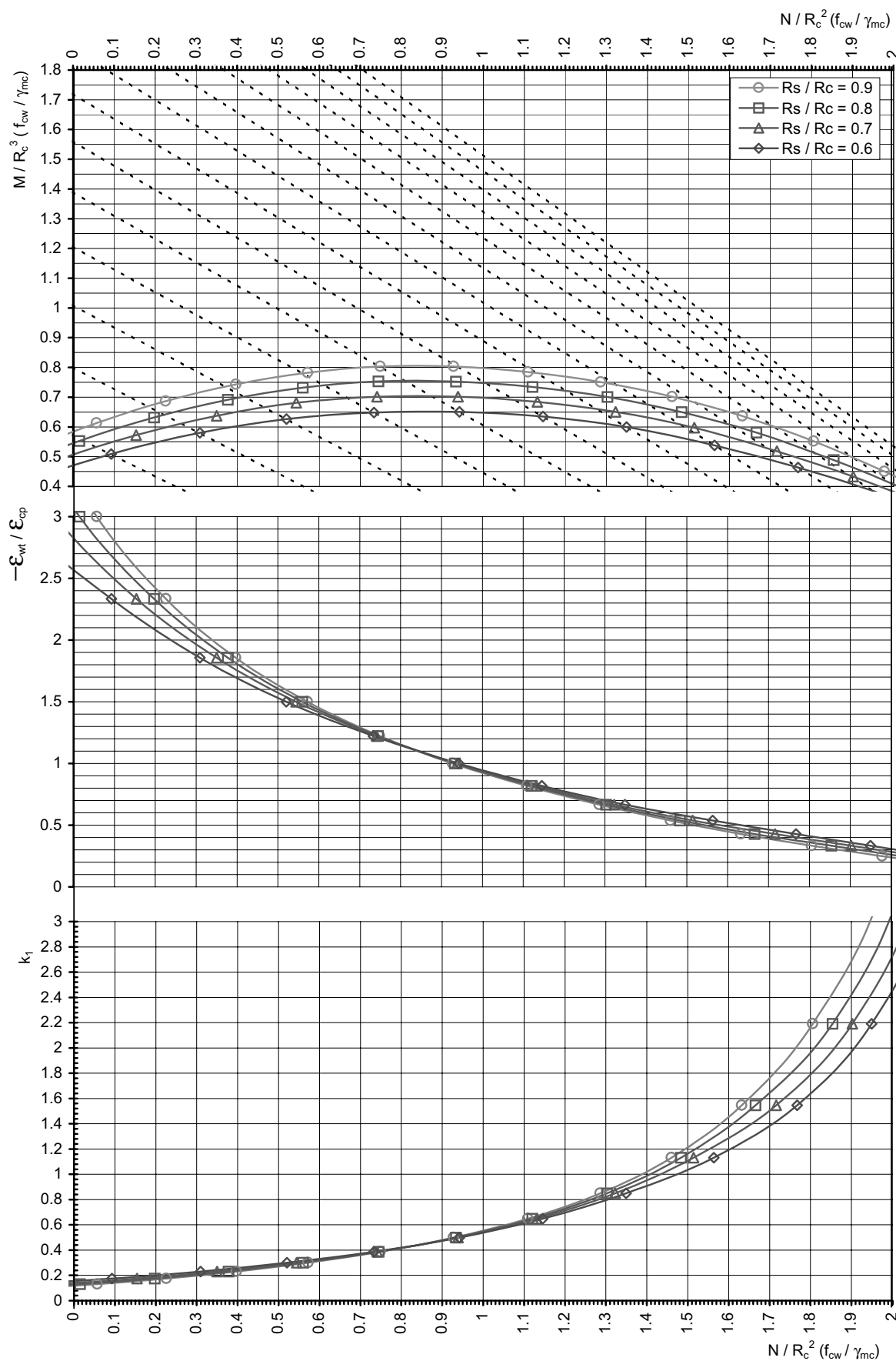
High Yield Steel, Unconfined Concrete



Circular Column Design Chart 15

$\omega = 0.25$

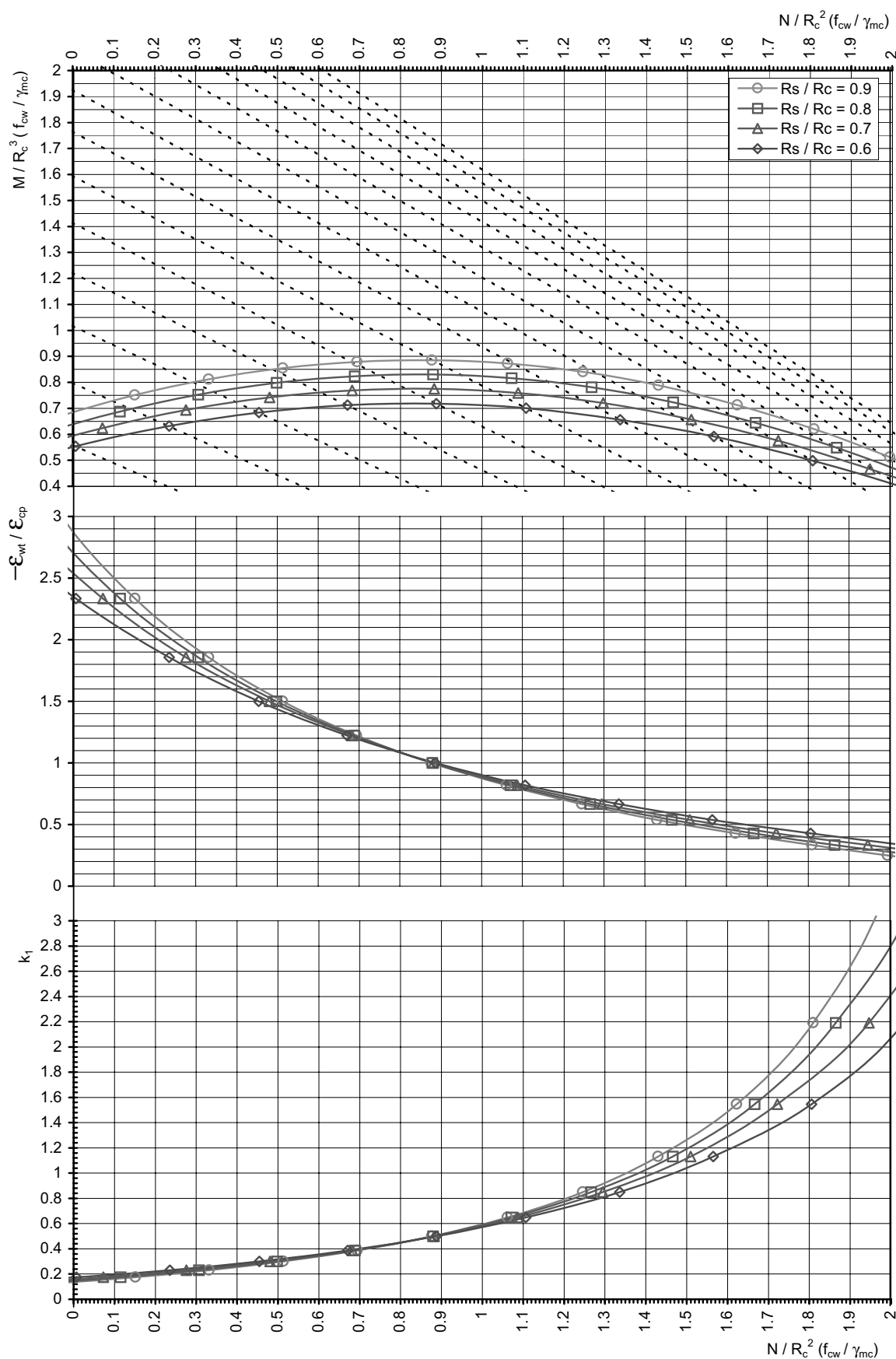
Mild Steel, Confined Concrete



Circular Column Design Chart 16

$\omega = 0.25$

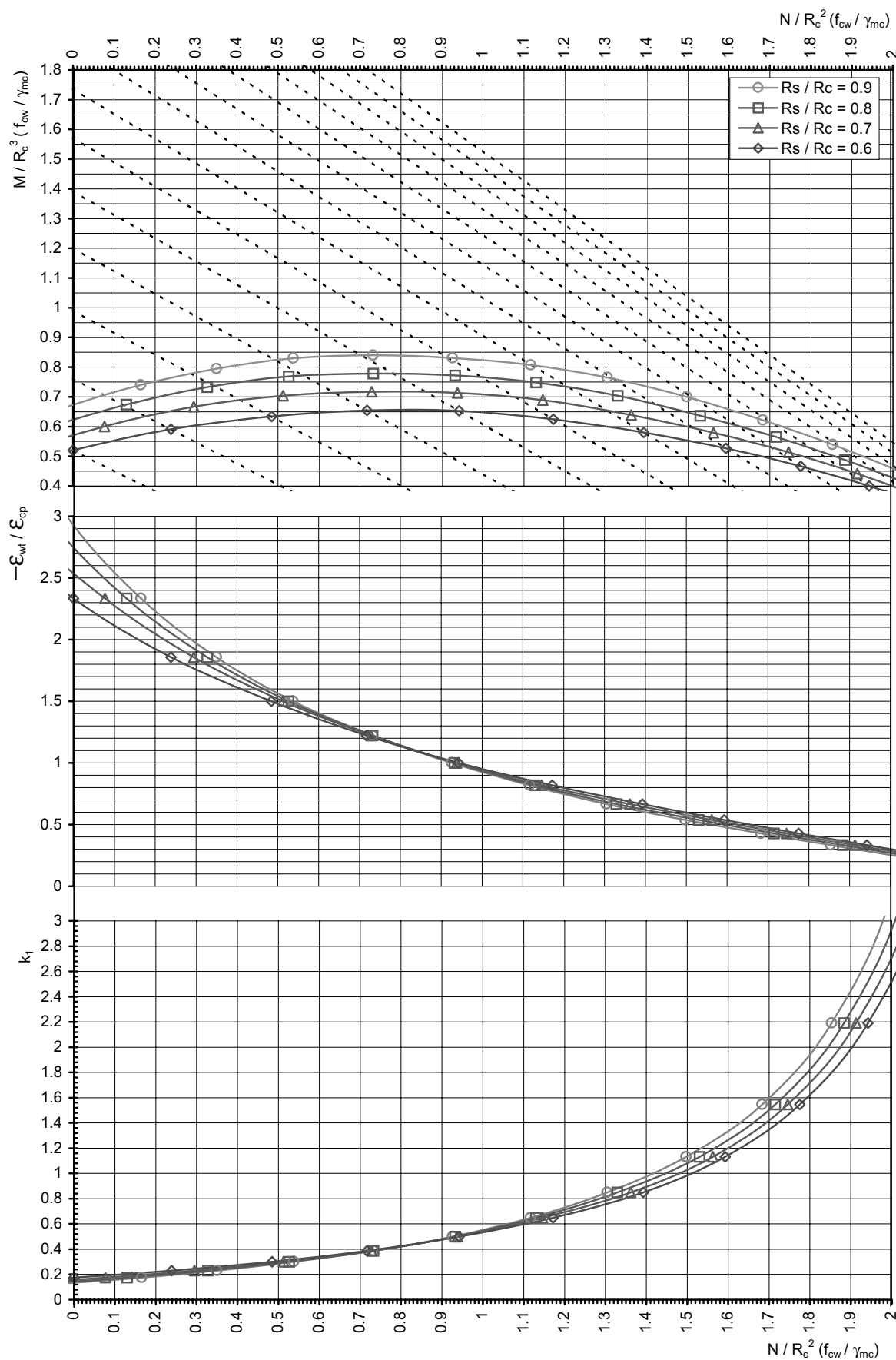
Mild Steel, Unconfined Concrete



Circular Column Design Chart 17

$\omega = 0.3$

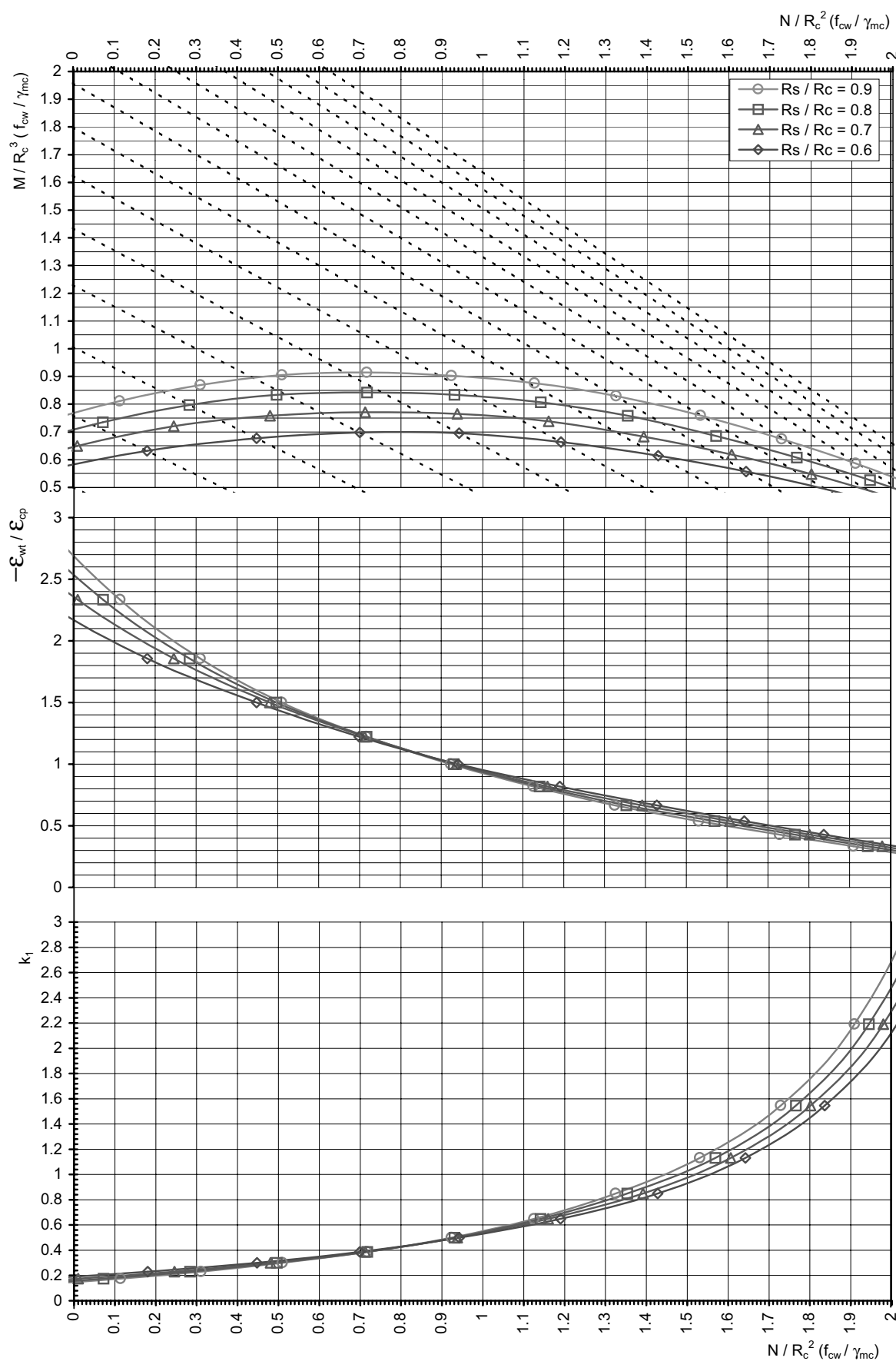
High Yield Steel, Confined Concrete



Circular Column Design Chart 18

$\omega = 0.3$

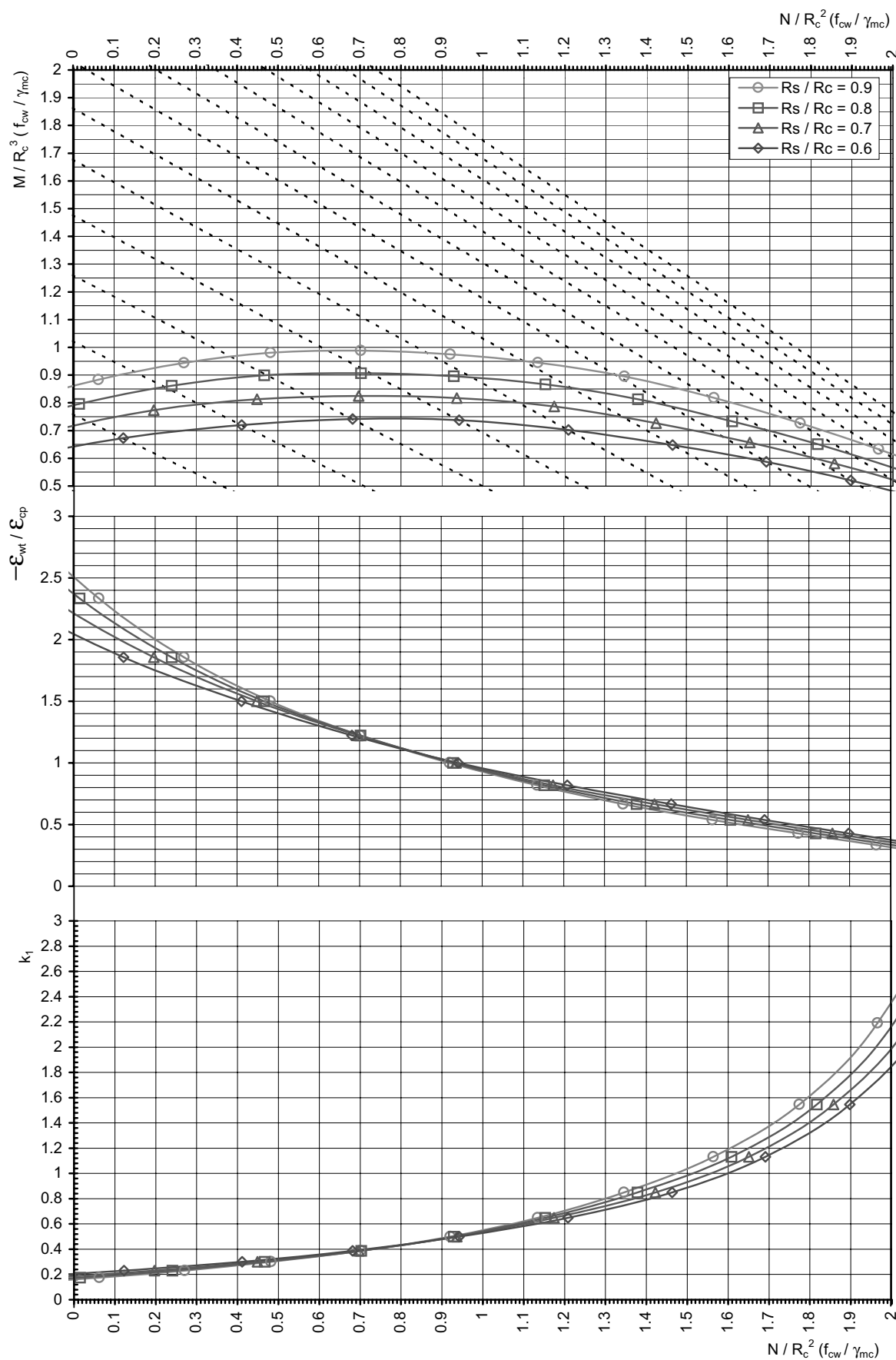
High Yield Steel, Unconfined Concrete



Circular Column Design Chart 19

$\omega = 0.35$

High Yield Steel, Unconfined Concrete



Circular Column Design Chart 20

$\omega = 0.4$

High Yield Steel, Unconfined Concrete



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