GRADE 500C REINFORCEMENT
GUARANTEED DUCTILITY

CI/SfB 28 Eq 4
Uniclass P227
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INTRODUCTION

When referring to reinforced concrete, ductility is often regarded as a complex concept. However, put simply, it refers to a building’s ability to dissipate energy and deform without brittle or sudden failure.

Regarding the steel bars used for concrete reinforcement (rebar), ductility can be defined as the ability of the bar to deform plastically without fracture, whilst maintaining its strength. This concept can be directly related to the non-linear behaviour of structures in which ductility plays an important role.

For many years engineers have recognised that continuous construction (i.e. statically indeterminant structures) achieves far greater load carrying capacity than similar simple structures (single span – statically determinant). This is due to a continuous structure’s ability to transfer potential overloading stresses to other less worked regions of the structure via rotation and deformation.

This behaviour can lead to significant deformation for only a small increase in load. The design of structural elements performing in this way goes far beyond the realms of linear elastic analysis.

Much testing has been carried out to understand this plastic performance better. Not only did this prove that the response was very different to that theoretically predicted, but it led to the development of a factor for flow or plasticity. In design, this factor for flow and plasticity is adopted in the form of moment redistribution.

In 1965 the basic principles of steel’s non-linear behaviour were published in CEB Bulletin No 52. Today the subject is again being studied to produce plastic design calculations based on better understanding, increased computing power and revised design standards. These standards have incorporated indirect methods of plastic calculation based on the redistribution of moments obtained from elastic analysis.

It should never be forgotten that the ability to take a reinforced concrete element beyond linear elastic analysis is almost entirely due to the ductility of the steel reinforcement.
All structures need ductility, as well as strength. In reinforced concrete, it is the reinforcing steel, which provides the structural element with ductility. Ductility of the element is its ability to fail by deflection or extensive cracking in an overload situation, without sudden catastrophic collapse.

Recent developments in design codes, such as Eurocode 2 (BS EN 1992-1-1:2004) have recognised the importance of the ductility of the reinforcing steel. New parameters for the specification of steel ductility have been introduced, in both Eurocode 2 and in material standards.

Eurocode 2 recognises three different reinforcing steel classes (A, B and C), based on ductility. Design rules now recognise the importance of steel ductility and provide designers with the means of using the additional ductility provided by high ductility steels.

The British Standard for reinforcing steels (BS 4449), which will be used in conjunction with the new European Standard (BS EN 10080), has been revised to reflect the three ductility classes of Eurocode 2. The characteristic yield strength has also been increased from 460 MPa to 500 MPa. The three grades introduced in BS 4449:2005 are B500A, B500B and B500C.

This brochure explains the importance of ductility in reinforced concrete structures, and the importance of ductile reinforcing steels. This is dealt with in some detail in the Appendix, written by Professor Andrew W. Beeby of Leeds University.

Celsa Steel (UK) Ltd, on the basis of extensive experience in group companies in Spain, has developed new steels for the UK market that fully meet all of the requirements of BS 4449 Grade B500C. This steel is called CELSA DUKTIL 500C.

The brochure describes CELSA DUKTIL 500C steels, their manufacture and properties.

CELSA DUKTIL 500C steels, new to the UK market, will give designers the ability to use high ductility steels, gaining the full design benefits of Eurocode 2, producing structures with added robustness and safety.
THE NEED FOR DUCTILITY IN REINFORCING STEELS

Strength is a characteristic of steel required in calculations, and recognised in standards and design codes, because steel plays an integral role in the mechanical behaviour of reinforced concrete.

Standards define strength requirements by means of two parameters: the elastic limit or **yield strength** (which is used in the steel grade designation) and the **ultimate tensile strength**.

Strength is a necessary requirement but it is not sufficient in itself to define the behaviour of reinforcing steel in concrete. There is also a requirement for **ductility**. Concrete is a brittle material, without ductility, and cannot be used for structural applications without reinforcement.

The ductility within a structure, something which concrete does not have, is provided by the steel reinforcement. Therefore the steel must be sufficiently ductile so that every reinforced concrete section, including structural elements, has the capacity to deform by an adequate amount.

Initially concrete was considered as the limiting factor for plastic rotation because of its low level of ductility. In general it was considered that the capacity for plastic rotation was independent of the type of steel used, because it was assumed that the concrete was the limiting factor. The steel was assumed to have sufficient ductility so that it did not limit rotation.

This presumption was made because at that time steel had comparatively low strength and high ductility owing to its chemical composition and the manufacturing processes employed. Later steels with higher strength and lower ductility were introduced, such as cold rolled wire (Grade A material).

The ductility of a steel is its capacity to deform under load without fracture once the yield strength has been exceeded.

Further studies have shown that the level of ductility of the steel influences and limits the rotation of plastic hinges.

In addition to the strength and ductility requirements, reinforced concrete needs sufficient bonding between steel and concrete to ensure the composite works efficiently and cracking is controlled.

Ductility is a property of reinforcing steel that is essential in those applications in which structures are subject to unexpected forces (seismic, dynamic, impact etc). In these situations, in which redistribution of moments is envisaged, it is not possible to calculate the loadings precisely owing to the nature of the loads or because of lack of knowledge about the effects on the structure.
In the case of a reinforced concrete structure subject to earthquakes, its behaviour is closely related to the ductility of its reinforcing steel. In this situation it is essential to know the capacity of the structure to react to exceptional loads when the elastic limit of the steel is exceeded.

Similarly, in those cases where forces and loads are difficult to quantify, it is desirable to design structures that resist loads that greatly exceed the generally accepted values used for design calculation without collapse due to deformation or major cracking.

If the structure is brittle, collapse occurs without prior warning, showing virtually no deformation and without cracking.

A ductile structure close to collapse shows its condition through pronounced deformation and cracking.

One of the benefits of ductility is the ability to redistribute loads, dissipating the applied energy to flexible elements such as beams. This property allows a more efficient use of concrete and steel because the most stressed zones can transfer load to less stressed areas.

The redistribution of moments is the ability to transfer negative moments to positive ones and vice versa and is recognised in design codes (ACI, Eurocode 2, CEB-FIP).

Significant redistribution of energy can only be achieved if the steel has high ductility.

Eurocode 2 allows the redistribution of moments as a function of the ductility class of the steel.

For ductility class A, redistribution is limited to 20%, whilst for classes B and C, up to 30% redistribution is allowed.

Eurocode 2 also allows plastic analysis for beams, frames and slabs where reinforcing steels of classes B and C are used. This is not allowed where class A steels are used.

Particular attention needs to be given to the specification of reinforcing steels for use in seismic design situations. In this case, the reversal of loading from tension to compression has a particularly destructive effect. Test methods are available which simulate seismic actions by subjecting reinforcing steel samples to cyclic loading under hysteresis loops.

The behaviour of reinforcing steel under such cyclic loading conditions is strongly dependent on ductility. Celsa Duktil 500C is compatible with Eurocode 8, for the design of seismic structures.
The behaviour of steel is characterised by its stress-strain relationship; the amount of deformation corresponding to an imposed load.

If a typical stress-strain relationship is analysed, there are two basic parts to the curve:

**elastic region**

In this region the strain (deformation) is linearly proportional to the applied load until the yield strength is reached. The elastic strain is recovered if the load is removed.

**plastic region**

Once the yield strength is exceeded, deformation is no longer proportional to load. Small increments of load produce larger plastic deformation, which cannot be reversed on unloading. Deformation continues with increasing load until the maximum (ultimate) load is reached (the maximum of the curve). Beyond this point, the load decreases as the cross section reduces in a local area before fracture (necking).

In hot rolled steels the identification of the elastic limit (yield strength) is very clear, owing to the existence of a yield point elongation. This is the flat portion of the curve which marks the change from elastic to plastic behaviour.

In contrast, the stress-strain curves for cold rolled steels lack a defined yield point, making it more difficult to establish the elastic limit. In this case codes and standards assume that the yield strength corresponds to the value of tensile stress required to produce a permanent deformation of 0.2%; the 0.2% proof stress. The determination of this value from the stress-strain curve is made by constructing a line parallel to the linear elastic portion with an offset of 0.2%. The intersection of this line with stress-strain curve gives the 0.2% proof stress.

Ductility in steel has traditionally been defined using two parameters obtained from the stress-strain $\sigma-\varepsilon$ diagram.

**Ultimate tensile strength / yield strength ratio ($f_t/f_y$)**

This is the ratio of the breaking stress or ultimate tensile stress ($f_t$) with the yield strength ($f_y$). It should be noted that $f_t$ and $f_y$ are the terms used in reinforced concrete nomenclature whilst the equivalent terms in steel standards are $R_m$ and $R_e$. 
Elongation to fracture on a 5D gauge length (A₅)
Traditionally this parameter has indicated the deformation capacity of steel. It is the value of the extension of a bar up to the point of fracture, measured over an initial gauge length of 5 times the bar diameter. In some specifications the initial gauge length is 10 times the bar diameter (called A₁₀).

The A₅ parameter is calculated from measurements made on the fractured sample. When the tensile test is carried out on the steel sample, and after fracture, the two halves of the test sample are butted together and the increase in length over the initial gauge length of 5 bar diameters is measured.

\[ A₅ = \frac{\text{new length} - \text{original length}}{\text{original length}} \times 100\% \]

The A₅ parameter was used to specify ductility of reinforcing steels in previous revisions of BS 4449.

Eurocode 2 and BS 4449:2005 now use another parameter to define ductility instead of A₅. This is called the total elongation at maximum force or uniform elongation \( \varepsilon_u \). In steel industry standards, this parameter is designated \( A_{gt} \).

\( \varepsilon_u \) or \( A_{gt} \) is defined as the uniform extension to maximum load or the percentage elongation which corresponds to the maximum stress on the stress-strain curve.

Uniform elongation is measured from the stress-strain graph by taking a horizontal tangent at the maximum of the stress-strain curve. The stress at this point is the ultimate tensile strength (\( f_t \) or \( R_m \)) whilst the strain is the uniform elongation (\( \varepsilon_u \) or \( A_{gt} \)).

Eurocode 2 specifies three ductility classes (A, B and C) with characteristic values of the two parameters, \( f_t/f_y \) (or \( R_m/R_e \)) and \( \varepsilon_u \) (or \( A_{gt} \)), which must be met simultaneously.

Nowadays it is possible to quantify ductility using a single parameter. Steels can be graded according to this characteristic which is based on the concept of steels of equivalent ductility.

The ductility of steel is related to the area under the stress-strain curve. This area represents the capacity of a steel to deform plastically up to its breaking point.

This area represents the stress and strain capacity of the material after reaching its elastic limit and is a measure of the energy absorbed in plastic deformation. It is termed the plastic energy factor.

\[ \text{STEEL DUCTILITY CLASSES IN EUROCODE 2} \]

<table>
<thead>
<tr>
<th>Class</th>
<th>Characteristic values</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>( f_t/f_y \geq 1.05 )</td>
</tr>
<tr>
<td>B</td>
<td>( f_t/f_y \geq 1.05 )</td>
</tr>
<tr>
<td>C</td>
<td>( f_t/f_y \geq 1.05 &lt; 1.35 )</td>
</tr>
</tbody>
</table>

\[ \text{PLASTIC ENERGY FACTOR} \]
The plastic energy factor, which is derived from the area below the stress-strain curve, allows the comparison of levels of ductility for different steels at the same yield strength level.

As shown in the diagrams, there are large differences in the ductilities of cold rolled steel Grade A, hot rolled steel Grade B and high ductility hot rolled steel Grade C.

The plastic energy factor is not currently recognised in codes or standards.

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The plastic energy factor of a hot rolled steel Grade C is greater than that of a hot rolled steel Grade B which is much greater than for a cold rolled steel Grade A.
COMPARISON OF DUCTILITY

ACCORDING TO STEEL GRADE

The British Standard for reinforcing steels, BS 4449, has been revised during 2005, to incorporate the following major changes:

- three grades have been introduced, aligned with the three ductility classes of Eurocode 2;
- the characteristic yield strength has been increased from 460 MPa to 500MPa;
- the standard has been aligned with the requirements of the European Standard, BS EN 10080.

The three grades in BS 4449:2005 have the following characteristic properties;

**B500A**

\[ f_y \geq 500\text{MPa} \quad (f_t/f_y) \geq 1.05 \quad \varepsilon_u \geq 2.5\%
\]

This grade is normally cold rolled steel produced by cold rolling of a plain hot rolled rod to produce ribbed wire. This is generally used in the production of welded fabric and is considered low ductility.

**B500B**

\[ f_y \geq 500\text{MPa} \quad (f_t/f_y) \geq 1.08 \quad \varepsilon_u \geq 5.0\%
\]

This grade is hot rolled steel in which the ribbed bar shape is formed in a hot rolling process. This grade is considered normal ductility.

**B500C**

\[ f_y \geq 500\text{MPa} \quad (f_t/f_y) \geq 1.15 \text{ to } 1.3 \quad \varepsilon_u \geq 7.5\%
\]

This grade is also hot rolled steel but using processes designed to retain more ductility. This grade is considered high ductility.

In addition to the above tensile properties all grades are required to meet common requirements for fatigue, bendability, weldability, bond and tolerances.

<table>
<thead>
<tr>
<th>TYPE OF STEEL</th>
<th>DUCTILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade B500A</td>
<td>Low</td>
</tr>
<tr>
<td>Grade B500B</td>
<td>Normal</td>
</tr>
<tr>
<td>Grade B500C</td>
<td>High</td>
</tr>
</tbody>
</table>

**COMPARISON OF STRESS-STRAIN CURVES FOR STEEL GRADES B500C, B500B AND B500A**

The greater the values of \( f_t/f_y \) (or \( R_m/R_e \)) and \( \varepsilon_u \) (or \( A_{gt} \)) the greater the ductility of the steel.
INTRODUCTION

Celsa Duktil 500C is a ribbed reinforcing steel for use in reinforced concrete. All products are manufactured by electric arc steelmaking, continuous casting and hot rolling processes.

In electric arc steelmaking a 100% scrap charge is melted by means of a high current electrical discharge from carbon electrodes. The molten steel is then tapped into a ladle before casting into water cooled copper moulds where the steel solidifies as it is continuously withdrawn from the mould. This produces a solid billet which is transferred to the bar mill where it is reheated in a furnace to a high uniform temperature in order to give the steel suitable plasticity for rolling.

In the hot rolling process the billet is passed through a series of rolling stands where its section is continuously reduced to the required dimensions. All the parameters affecting the rolling process, such as temperature, rolling speed and volume of cooling water, are constantly and carefully controlled. The rib pattern and identification marks are rolled on to the product in the final rolling stand using a specially notched pair of rolls. After this final rolling stand, the bar is subjected to the Quench and Self Temper (QST) accelerated cooling process in which the mechanical properties are achieved.

Celsa Duktil 500C complies with all the specifications and ductility characteristics required by BS 4449 Grade B500C. The parameters of ductility of this grade of steel, shown here, meet the requirements for high ductility (class C) steel as defined in Eurocode 2. This means that Celsa Duktil 500C is appropriate for all those situations in which the benefits of high ductility are required.

High ductility is a characteristic of steel for reinforced concrete which is highly desirable in most cases and essential in certain situations, for example where structures are subject to seismic demands.

TENSILE PROPERTIES

Celsa Duktil 500C is a high ductility reinforcing steel:

- **500** indicates the value of the characteristic yield strength, expressed in MPa (or N/mm²);
- **C** indicates the steel’s very high ductility characteristics.

The tensile properties of Celsa Duktil 500C are:

<table>
<thead>
<tr>
<th>Characteristic Tensile Properties - Celsa Duktil 500C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength ($f_y$)</td>
</tr>
<tr>
<td>Stress ratio: Tensile strength/Yield strength ($f_t/f_y$)</td>
</tr>
<tr>
<td>Uniform elongation (ε_u)</td>
</tr>
<tr>
<td>Relationship $f_y$ (actual)/$f_y$ (nominal)</td>
</tr>
</tbody>
</table>

* These values are important because if the steel is overstrength, that is its actual strength exceeds the nominal by a significant amount, the formation of plastic hinges during deformation is inhibited.
BEND PERFORMANCE

Celsa Duktil 500C meets the bend requirements of BS 4449:2005 Grade B500C. This is defined by a rebend test, with the following mandrel diameters:

- \( d \leq 16\text{mm} \): \( 4d \)
- \( d > 16\text{mm} \): \( 7d \)

FATIGUE PERFORMANCE

Celsa Duktil 500C steels meet the fatigue requirements of BS 4449:2005 Grade B500C. Test are carried out on full section bars using a sinusoidal tensile load as follows:

All tests are required to survive for 5 million stress cycles under these loading conditions.

The fatigue performance of Celsa Duktil 500C meets the requirements of the National Annex of Eurocode 2, and the requirements of BS 5400 Pt 4 (concrete bridges).

The procedure is carried out at room temperature with a frequency of up to 200Hz.

The test is continued until 5 million stress cycles have been reached or until the fracture of the test sample.

<table>
<thead>
<tr>
<th>SIZE( (\text{mm}) )</th>
<th>MAX STRESS (MPa)</th>
<th>MIN STRESS (MPa)</th>
<th>No. CYCLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \leq 16 )</td>
<td>250</td>
<td>50</td>
<td>5 million</td>
</tr>
<tr>
<td>20</td>
<td>231</td>
<td>46</td>
<td>5 million</td>
</tr>
<tr>
<td>25</td>
<td>212</td>
<td>42</td>
<td>5 million</td>
</tr>
<tr>
<td>32</td>
<td>200</td>
<td>40</td>
<td>5 million</td>
</tr>
<tr>
<td>40</td>
<td>187.5</td>
<td>37.5</td>
<td>5 million</td>
</tr>
<tr>
<td>50</td>
<td>187.5</td>
<td>37.5</td>
<td>5 million</td>
</tr>
</tbody>
</table>

BOND PERFORMANCE

Celsa Duktil 500C meets the bond requirements of BS 4449:2005 Grade B500C, defined by characteristic relative rib area \( (f_r) \) as follows:

- \( 6 < d \leq 12 \) \( f_r \geq 0.040 \)
- \( d > 12 \) \( f_r \geq 0.056 \)

Reinforcing steels with these values of relative rib area are deemed to meet the bond requirements for design according to Eurocode 2.

WELDABILITY

Because of its carefully controlled chemical composition, Celsa Duktil 500C has a carbon equivalent below 0.50%, when calculated according to the following formula:

\[
\%C_{eq} = \%C + \frac{\%\text{Mn}}{6} + \frac{\%\text{Cr}}{5} + \frac{\%\text{Mo}}{15} + \frac{\%\text{V}}{5} + \frac{\%\text{Ni}}{5} + \frac{\%\text{Cu}}{15}
\]

This meets the requirements of BS 4449:2005 and BS EN 10080 for the definition of a weldable steel.

Celsa Duktil 500C steels can be welded using all common welding processes. Reference should be made to BS 7123 for guidance on welding of reinforcing steels.
### Table of Sections and Mechanical Capacities

<table>
<thead>
<tr>
<th>NOMINAL DIAMETER (mm)</th>
<th>NOMINAL WEIGHT / m</th>
<th>STEEL SECTION IN mm² AS A FUNCTION OF BAR SPACING</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>50.3</td>
<td>0.395</td>
</tr>
<tr>
<td>10</td>
<td>78.5</td>
<td>0.617</td>
</tr>
<tr>
<td>12</td>
<td>113.1</td>
<td>0.888</td>
</tr>
<tr>
<td>16</td>
<td>201.1</td>
<td>1.578</td>
</tr>
<tr>
<td>20</td>
<td>314.2</td>
<td>2.47</td>
</tr>
<tr>
<td>25</td>
<td>490.9</td>
<td>3.85</td>
</tr>
<tr>
<td>32</td>
<td>804.2</td>
<td>6.31</td>
</tr>
<tr>
<td>40</td>
<td>1256.6</td>
<td>9.86</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NOMINAL DIAMETER (mm)</th>
<th>NOMINAL WEIGHT / m</th>
<th>STEEL SECTION IN mm² ACCORDING TO NUMBER OF BARS</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.395</td>
<td>21.85</td>
</tr>
<tr>
<td>10</td>
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<td>34.15</td>
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<tr>
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<td>0.888</td>
<td>49.17</td>
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<tr>
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<td>1.578</td>
<td>87.42</td>
</tr>
<tr>
<td>20</td>
<td>2.47</td>
<td>136.59</td>
</tr>
<tr>
<td>25</td>
<td>3.85</td>
<td>213.42</td>
</tr>
<tr>
<td>32</td>
<td>6.31</td>
<td>349.67</td>
</tr>
<tr>
<td>40</td>
<td>9.86</td>
<td>546.36</td>
</tr>
</tbody>
</table>

MECHANICAL CAPACITY IN kN ACCORDING TO NUMBER OF BARS (Tensile loading) - $\gamma_s = 1.15$

<table>
<thead>
<tr>
<th>NOMINAL DIAMETER (mm)</th>
<th>NOMINAL WEIGHT / m</th>
<th>MECHANICAL CAPACITY IN kN</th>
<th>STEEL SECTION IN mm² ACCORDING TO NUMBER OF BARS</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.395</td>
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<td>40</td>
<td>9.86</td>
<td>546.36</td>
<td>9.86</td>
</tr>
</tbody>
</table>
INTRODUCTION

Celsa Duktil 500C reinforcing bars are supplied in sizes from 8mm to 40mm, in lengths from 6m to 18m, and in standard bundle weights of 2 tonnes.

Nominal bar sizes are 8, 10, 12, 16, 20, 25, 32 and 40mm.

Section tolerances on Celsa Duktil 500C bars meet the requirements of BS 4449:2005 as follows:

<table>
<thead>
<tr>
<th>BAR DIAMETER</th>
<th>TOLERANCE (weight/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤8mm</td>
<td>±6.0%</td>
</tr>
<tr>
<td>&gt;8mm</td>
<td>±4.5%</td>
</tr>
</tbody>
</table>

LABELLING

All bundles of Celsa Duktil 500C bars are labelled with steel tallies giving the following information:

- Celsa name and logo
- Bundle number
- Cast number
- Bundle weight
- Material grade
- Date of rolling

RIB GEOMETRY

The rib pattern of Celsa Duktil 500C bars complies with that for BS 4449:2005. The bar contains two rows of ribs, one on each side of the bar, arranged in a herringbone pattern. In each row of ribs, alternating ribs are at low or high angles to the axis of the bar. For improved bending consistency, the bar contains no significant longitudinal ribs.

IDENTIFICATION

The country of origin and works number are identified by rolled on marks between normal transverse ribs. All Celsa Duktil 500C bar is identified with country number 5, and works number 12, as shown below. The dash at the end of the mark identifies the bar as being 500 grade.

TEST CERTIFICATION

All despatches of Celsa Duktil 500C bars are accompanied with a full mill test certificate, including the results of chemical analysis, and all the mechanical tests according to BS 4449:2005.
CELSA DUKTIL 500C REINFORCING COILS

INTRODUCTION

In recent years the process of bending and tying steel for reinforced concrete has advanced through the greater use of automatic bending machines that not only reduce cost but improve the quality of the shapes produced.

The use of such new technology has created a need for coiled reinforcing steel with characteristics adapted for use with this type of machinery. Celsa Duktil 500C is the solution.

Celsa Duktil 500C reinforcing coils are supplied in sizes from 8mm to 16mm in standard coil weights of 2 tonnes.

Nominal sizes are 8, 10, 12 and 16mm.

Section tolerances on Celsa Duktil 500C bars meet the requirements of BS 4449:2005 as follows.

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<td>±4.5%</td>
</tr>
</tbody>
</table>

RIB GEOMETRY

The rib pattern for Celsa Duktil 500C bars complies with that for BS 4449:2005 grade B500C. Seen in cross section, coils of Celsa Duktil 500C have four sides with rounded corners. There is a row of transverse ribs on each face so that the overall shape is approximately circular. This shape is designed to give consistent bending through automatic machines.

IDENTIFICATION

The country of origin and works number are identified by rolled on marks between normal transverse ribs. All Celsa Duktil 500C coil is identified with country number 5, and works number 12, as shown below. The dash at the end of mark identifies the bar as being 500 grade.

LABELLING

All Celsa Duktil 500C coils are labelled with steel tallies giving the following information:

- Celsa name and logo
- Bundle number
- Cast number
- Bundle weight
- Material grade
- Date of rolling

TEST CERTIFICATION

All despatches of Celsa Duktil 500C coil are accompanied with a full mill test certificate, including the results of all mechanical tests according to BS 4449:2005.
ADVANTAGES OF USING COILED CELSA DUKTIL 500C

There are considerable advantages in using coiled Celsa Duktil 500C:

- geometry with four ribbed faces. This gives more consistent bending in different directions. In straightening there is a reduced tendency for the material to twist. When bending there is a reduced tendency for the material to twist out of plane. As a consequence closed forms such as links are produced with less distortion and twisting of the legs;

- bending machines can be less powerful;

- reduced wear on the machine rolls;

- there is less damage or distortion of the ribs during straightening and bending because of the outside envelope of the shape being approximately circular;

- using coils of Celsa Duktil 500C gives excellent results with machines used for the shaping of reinforcement;

- coiled Celsa Duktil 500C allows the creation of complex shapes for concrete reinforcement.
APPLICATIONS FOR CELSA DUKTIL 500C SPECIAL DUCTILITY STEEL

Celsa Duktil 500C should be used in applications where high ductility is either desirable or essential. These include:

Structures where calculations have been worked using non-linear methods and structures that allow limited energy dissipation. Structures need to have steel reinforcement with sufficient ductility to guarantee the required capacity for the distribution of applied forces.

Structures subject to forces that are difficult to quantify because of the nature of those forces or due to lack of knowledge about those forces or their effects on the structure, such as:

- dynamic loading;
- explosions;
- sudden impact;
- compressive and tensile forces;
- unforeseen or accidental overloading.

The use of high ductility steel is necessary in buildings where catastrophic failure must be prevented.

Structures in which there is a high risk of fire. If by the action of fire, a section of a ductile structure forms plastic hinges and deforms, the adjacent sections adapt and delay the collapse of the remaining structure rather than collapsing catastrophically.

As long as a structure has a robust design, the greater the ductility of the steel, the greater the distribution of loads. This will lead to an increase in the formation of plastic joints, rather than a failure mechanism.

Structures in which a change of use is foreseen and older structures that require restoration. In such situations a limited redistribution of loads can be achieved with the purpose of achieving maximum benefit from the steel's ductility. Restoration and refurbishment can be carried out to maximise the capacity of the original structure to absorb different load conditions.

Seismic Design. When subjected to seismic forces, the manner in which the structure reacts is highly dependent on the ductility of the steel used in its construction. Under such stresses the behaviour of the structure and its ability to distribute energy are fundamental because the elastic region of the steel is exceeded.
ADVANTAGES OF USING 500C HIGH DUCTILITY STEEL

Ductility is a necessary characteristic of steels used to reinforce concrete. It is very desirable in all cases and essential in some applications. Celsa Duktil 500C has greater ductility than steels of the same strength of grades 500A and 500B and provides these advantages:

• allows the formation of plastic hinges in a stressed structure that have sufficient rotational capacity to deform and dissipate the applied load until the collapse mechanism of the structure is reached;

• provides the best solution for structures subject to earthquakes owing to high dissipation of energy;

• allows the application of non-linear design calculations that allow for redistribution of moments and consequent optimum use of the steel reinforcement;

• in well designed statically non-determinant structures, high ductility steels facilitate the distribution of loads.

The use of high ductility steel prevents the sudden catastrophic collapse of structures, reducing loss of life and other damage.

With the availability of new technology, the Celsa Group has been able to develop a new type of steel, Celsa Duktil 500C, that provides the benefits required.
WHY WE NEED DUCTILITY IN REINFORCED CONCRETE STRUCTURES

Professor Andrew W. Beeby
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Published in May 2004

Our understanding of the influence of ductility on structural design has increased considerably beyond that available when, for example, BS 8110 (1) was drafted. When Eurocode 2 (2) is finally published for use (probably sometime in 2004), it will include a classification of the ductility of reinforcement. This classification will define the nature of the design processes which may be used with a particular class of reinforcement. The classification is as follows.

**Class A:** \((f_t/f_y)k \geq 1.05\) \(\varepsilon_{uk} \geq 2.5\%

**Class B:** \((f_t/f_y)k \geq 1.08\) \(\varepsilon_{uk} \geq 5\%

**Class C:** \((f_t/f_y)k = 1.15-1.35\) \(\varepsilon_{uk} \geq 7.5\%

where \((f_t/f_y)k\) is the characteristic value of the ratio of the ultimate tensile strength \((f_t)\) to the yield strength \((f_y)\) and \(\varepsilon_{uk}\) is the characteristic value of the strain at maximum stress (also sometimes called uniform elongation). These parameters are illustrated in Figure 1. In the past, BS 4449 (3) only defined the elongation to failure as a measure of ductility but in the most recent amendment (1997), two ductility classes are defined: 460A and 460B. In addition to the elongation to failure, these classes have the same ductility requirements as Class A and Class B defined in the Eurocode and set out above. A recent paper by Franks (4) sets out the current situation in more detail.

Class A reinforcement can only be used in EC2 design, where moment redistribution is less than 20% and may not be used where any plastic method of analysis has been employed. Class B reinforcement may be used with plastic methods of analysis and for amounts of redistribution up to 30%. Class C reinforcement can be used interchangeably with Class B, and is a requirement where there are seismic conditions. Current production methods normally result in reinforcement of Class B or C for bars of above 16mm diameter.

However, production methods for smaller bars, which are mostly produced via a coil route, may lead to reinforcement of Class A or, occasionally, below. CELSA Steel (UK), who have taken over the plant once operated by ASW, and are now the UK’s largest manufacturer of reinforcing steels, have developed a method of using the Tempcore process for coil, and expect to supply Class C reinforcement in all sizes with a characteristic yield strength of 500MPa.

These changes, in code provisions and manufacturing processes, make it an appropriate moment to re-examine ductility and consider what its benefits are. Ductility is generally recognised as being a ‘good thing’ but the rationale for quantifying its benefits only exists in very limited areas, notably the relationship between ductility and the amount of redistribution permitted in analysis for the ultimate limit state. Since this last item has been the subject of much research, it will be considered first.
Ductility and redistribution

The basic issues are illustrated for the case of a uniformly loaded fixed ended beam in Figure 2. Under low loads, the beam will behave more or less elastically until a load is reached which just causes the reinforcement at the supports to yield. The beam does not collapse under this load but the moment at the support cannot increase above the yield moment.

Further loading results in a more rapid increase in the moment at mid-span until a load is reached which will cause yield at this point. Once yield has been reached at both supports and at mid-span, a mechanism will have formed and no further load can be carried. Study of the deflected shape of the beam at ultimate load will show that the support section has to rotate through an angle $\theta$ under constant moment. In practice, this rotation occurs over a finite length within which extensive cracking will develop. This region is called a ‘plastic hinge’.

In a beam such as that shown in Figure 2, the full ultimate load can only be reached if the support sections (the plastic hinges) are sufficiently ductile to be able to accommodate a rotation of $\theta$. Reinforced concrete sections are not necessarily sufficiently ductile and a means has to be found to ensure that the required rotation does not exceed the rotation capacity of the section.

The analytical device commonly used to ensure this is ‘redistribution’. Analysis under the ultimate loads is carried out elastically. The support moments can then be reduced and the mid-span moment increased so that the resulting bending moment diagram remains in equilibrium with the loads. It can be shown that the percentage reduction in the support moment is proportional to the required rotation of the support section.

Extensive research has shown that a relationship exists between the ultimate rotation capacity of a section and the ratio of the neutral axis depth to the effective depth ($x/d$). Practical rules can conveniently be devised giving a relationship between percentage redistribution and $x/d$. Both BS 8110 and the Eurocode include such relationships.

In the Eurocode, the design relationships vary depending on the ductility of the reinforcement. The Eurocode redistribution rules for concrete with a cube strength below 60MPa are shown in Figure 3.
APPENDIX

Ductility and plastic methods of design
A basic assumption of plastic methods of analysis, either of a structure or more locally, is that the materials are infinitely ductile. While infinite ductility is not actually required, plastic methods provide no check on how much ductility is actually needed in any particular case.

If limitations in the ductility of the material might invalidate the calculation then either some additional, independent, check on the ductility is required or plastic methods must be avoided.

In practice, we may not actually be aware that a method we are using is plastic. The classic form of plastic analysis used in reinforced concrete is Yield Line Analysis for slabs. Probably few of us actually use this method directly and, where we do, BS 8110 provides some limited guidance to avoid an excessive ductility requirement.

The average user of BS 8110 may, however, not be aware that the moment coefficients given for two-way spanning slabs have been derived from yield line analysis. The average code user may also not be aware that many of the methods used for section design, as opposed to analysis, are also plastic. Strut-and-tie models or truss analogy methods are intrinsically plastic as they assume that it is possible for the internal forces to redistribute themselves from an elastic situation to the arbitrarily chosen arrangement of struts and ties. It can be argued that design for shear is plastic.

Design of sections for flexure is, more clearly, plastic, though with a check on the strain capacity of the concrete and, indirectly, through neutral axis limits, on the strain in the reinforcement. We are thus more dependent on plastic methods than we may generally be aware. We generally rely on the formulation of the methods in the code or on detailing rules to ensure that the ductility is adequate. It is probably true, however, that even the experts on many of these methods could not define reliably what ductility is actually required and hence at what stage the ductility of reinforcement could become insufficient.

Ductility and Robustness
This is the most difficult issue to deal with. We all agree that structures should be robust but what we actually mean by this is rather obscure. The nearest we come to a definition of robustness is the principle that the damage suffered by a structure as the result of an unforeseen event should not be disproportionate to the cause. This does not give the designer much help in designing his structure as, unfortunately, unlike strength, we have not yet developed any means of quantifying the concept of robustness.

Despite this problem of quantification, the basic requirements for a robust design are fairly clear. If part of a structure is damaged by some accident, for example, a gas explosion, then the structure should hang together and not completely collapse. We achieve this by tying the members together so that, even in a damaged state, the structure does not fall apart. Codes (eg. BS 8110) provide arbitrary rules for the location and strength of the ties. What is not made clear is that, for the structure to hang together after being damaged, the ties must also be ductile. In the event of an accident such as an explosion, a non-ductile

![Figure 4. Schematic ultimate requirements for load and energy absorption](image-url)
tie would simply rupture during the accident. What level of ductility is required has, as far as is known, not been investigated. Beeby, in a paper in the Structural Engineer (5) put forward a possible basis for the quantification of robustness. The concept arose from the perception that a structure needs to be capable of withstanding two quite different and independent sets of actions:

a. the structure should be able to support a defined ultimate load and;

b. the structure should be able to absorb, without collapse, a defined energy input.

It was suggested in (5) that the required energy absorption should be a function of the volume of the member or members or structure considered. The basic concept is illustrated in Figure 4. This concept has yet to be elaborated into a full design proposal but does seem to provide a logical framework for a rational and quantitative treatment of robustness. It will be seen that it also defines the ductility requirements related to robustness of all parts of a structure.

**Discussion**

This paper has tried to illustrate the importance of ductility in the design of reinforced concrete for the ultimate limit state. Unfortunately, when assessing the relative economy or efficiency of a design or a particular material, our current methods of design can only take account of those aspects of behaviour which can be quantified. This does not mean that aspects of behaviour which have not been quantified are less important; it may simply mean that the science has not developed to a level where quantification is possible. This is the case for many of the aspects of ductility discussed in this paper and, in particular, the issue of robustness. It is only in the case of the analysis of framed structures that detailed quantitative requirements for ductility are currently defined. In all other situations, it is simply assumed that sufficient ductility exists if the reinforcement meets the current specifications. Unfortunately, this means that the benefits of specifying reinforcement with a higher ductility, though they clearly exist in terms of a reduction in risk, are not quantifiable and are therefore less likely to be considered. We are constantly developing designs which are more sensitive; possibly with greater, but unknown and unquantified, requirements for ductility. In this circumstance, one can only feel that the greater the ductility of the materials being used, the greater confidence one can have in the overall performance of the structure, under whatever foreseen or unforeseen circumstances may occur.

**References**

(1) BS 8110: Structural Use of Concrete

(2) CEN. prEN 1992-1-1 (Final draft):


(5) Beeby, A. W. Safety of structures and a new approach to robustness.
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