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Design by test approach for Fibre Reinforced Precast Segment

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Design by test approach for Fibre Reinforced Precast Segment

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The aim of this white paper is to present a common design approach for the use of fiber-reinforced concrete (FRC), supported by test methods and performance class requirements.

1. INTRODUCTION TO FIBER-REINFORCED CONCRETE

Fibers are an outstanding material to reinforce precast concrete segments for tunnel linings. They can be used as “fiber only” and thus the primary reinforcement, or in combination with conventional (bar) reinforcement, in which case they are referred to as a combined solution or secondary reinforcement.

Fiber-reinforced concrete (FRC) segments have been used successfully in a large number of reference projects throughout the world. These use cases consistently report the following benefits of FRC:

- Excellent durability
- Minimal damage from handling and installation procedures
- Reliable and high performance in the relevant Serviceability Limit State (SLS) and Ultimate Limit State (ULS) specifications
- Less waste than conventionally reinforced concrete
- Reduced overall manufacturing costs compared to conventionally reinforced concrete.

FRC and SLS/ULS specifications

Structural design of FRC elements is based on the post-cracking residual strength provided by fiber reinforcement. Other cases, like early age crack control or fire resistance, are considered non-structural uses of FRC.

For structural use, a minimum mechanical performance of FRC must be guaranteed. Fibers can be used to improve the behavior at Serviceability Limit State (SLS) since they can reduce crack spacing and crack width, thereby improving durability.

Fibers can also be used to improve behavior at Ultimate Limit State (ULS) where they can partially or totally substitute conventional reinforcement. The mechanical properties of a cementitious matrix are modified when fibers are added. However, elastic properties and compressive strength are not significantly affected by fibers, unless a high percentage of fibers is used.

2. MODEL CODE 2010 AND FRC

Thanks to the publication of European standards that specifically deal with fibers, and the existence of international design guidelines such as Model Code 2010, designers are able to follow a clear design approach to support their use of FRC.

Moreover, in recent years, multiple research studies and full-scale tests have been carried out in various countries on the behavior of FRC. These have also contributed to a better characterization of FRC and an improved understanding of the behavior of this material, which together have enabled designers to specify project-specific minimum performance requirements.

Model Code 2010 is the most comprehensive code on concrete structures. It covers their complete life cycle from conceptual design, dimensioning, construction and conservation through to dismantlement. It is edited by fib (fédération internationale du béton / international federation for structural concrete). fib Model Code 2010 was produced through the exceptional efforts of participants in 44 countries from five continents.

In Model Code 2010, FRC is recognized as a new material for structures. The code allows designers to identify effective constitutive laws for designs incorporating FRC, and describes the major contribution of FRC in terms of performance and orientation for structural uses. It takes into account basic concepts such as structural characteristic length and factors related to fiber distribution, as well as structural redistribution benefits. The code also addresses specific problems relating to tunnel boring machine thrusts. Lastly, Model Code 2010 will be used as a basis to introduce FRC in the Eurocode under preparation.

Three key chapters in Model Code 2010 that are of particular relevance to FRC are:

- §5 Materials
    - 5.6 Fibers / Fiber Reinforced Concrete
- §6 Interface Characteristics
    - 6.4 Concrete to steel
- §7 Design
    - 7.7.1 Verification of safety and serviceability of FRC structures

3. TEST METHODS AVAILABLE TO SUPPORT FIBRE REINFORCED PRECAST SEGMENT DESIGN PROCESSES

In recent years, significant interest has grown in the use of FRC in precast tunnel segments, particularly when tunnel boring machines (TBMs) are used [Model Code 2010 §5]. The bended shape of these segments leads to the use of ordinary reinforcement with complex detailing. These structures are mainly stressed during the construction phase rather than in the service stage. Consequently, it is important to maintain their structural integrity – by limiting concrete cracking – mainly in the curing and assembly steps, when segments can be subjected to impact loads during handling and to point loads from the TBM rams. Fiber reinforcement is particularly suitable to achieve this goal [Model Code 2010 §6]. Other advantages in the use of FRC in tunnel segments are related to the possibility to remove cathodic protection, when traditional reinforcement is avoided. This is because the fibers are dispersed in the concrete matrix and the absence of contact between them does not allow the onset of current.

To support FRC design processes, three different kinds of experimental tests should be performed:

- **Material property tests** according to EN 14651
- **Bending tests** to evaluate the bearing capacity under flexure that can occur during transitional stages (i.e. during demolding, storage and moving) and in the field due to asymmetrical soil pressure
- **Point load tests** to reproduce the action of the TBM on the segment during the excavation process.

Material property tests

The tensile behavior of the materials was characterized by performing bending tests on a notched beam. The tests were performed according to the EN 14651 European code, which is the reference standard for the CE label of steel and for ISO certification.

The compressive strength of the materials was measured by a testing cube with a side of 150 mm. For every cast made for the production of every single segment, three beams were produced. In agreement with EN 14651, nominal strengths corresponding to four different crack mouth opening displacement (CMOD), namely 0.5, 1.5, 2.5 and 3.5 mm, were evaluated.

Figure 1 shows a typical result of the beam tests with significant strength values. FL is peak force,

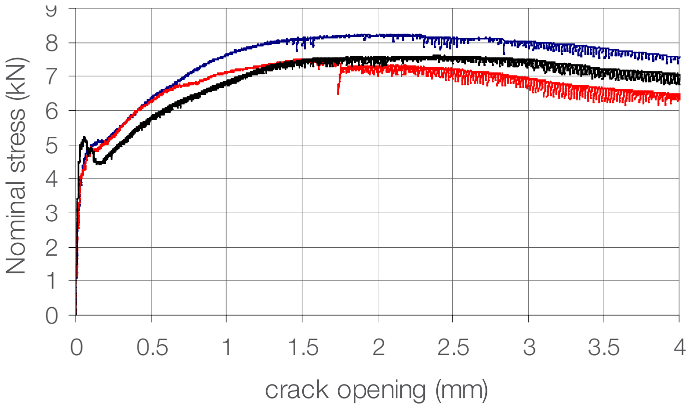

Figure 1. Typical results of beam tests of FRC according to EN 14651.

f_{R1} and f_{R3} are the stresses related to CMODs equal to 0.5 and 2.5 mm respectively. These values are the reference ones for the segment design performed according to the *fib* Model Code 2010 prescriptions.

To dimension a steel fiber-reinforced concrete segment, a reference test methodology needs to be adopted for the characterization of performance. In addition to the mechanical performance, various properties of the FRC can be specified.

Material classification is an important requirement for structural design. When referring to ordinary concrete, designers choose its strength, workability or exposition classes that have to be provided by the concrete producer. The compressive strength of FRC is not particularly influenced by the presence of fibers (up to a volume fraction of 1%) so that the classification for plain concrete can be adopted.

In accordance with section 5.6 of Model Code 2010 and in the absence of an alternative procedure whose operation has been validated, the beam tests according to standard EN 14651 published in November 2005 “Test method for metallic fibered concrete: measuring the flexural tensile strength (limit of proportionality LOP, residual)” were used for the characterization of FRC.

The behavior in tension of FRC was evaluated in terms of residual flexural tensile strength values, which are determined based on the load-crack opening curve or the load-deflection curve, which is obtained by applying a center-point load on a simply supported notched prism.

The test results which need to be expressed are the limit of proportionality (LOP) and the residual flexural strength (see Figure 2).

The limit of proportionality $f_{ct,L}^{f}$ is calculated as:

$$f_{ct,L}^{f} = \frac{3}{2} \cdot F_{L} \cdot \frac{l}{bh^2}$$

where F_L is the maximum load between CMOD 0 and 0.05 mm or deflection 0 and 0.08 mm.
The residual flexural strength $f_{R,x}$ needs to be evaluated at four different displacements:

$$f_{R,i} = \frac{3}{2} \cdot F_{R,i} \cdot \frac{l}{bh^2}$$

where $F_{R,i}$ is the residual load at:
- i = 1: CMOD = 0.5 mm or deflection 0.47 mm
- i = 2: CMOD = 1.5 mm or deflection 1.32 mm
- i = 3: CMOD = 2.5 mm or deflection 2.17 mm
- i = 4: CMOD = 3.5 mm or deflection 3.02 mm

l = the span between the supports (nominal distance 500 mm)
b = the width of the concrete sample (nominal value 150 mm)
h = the residual height of the concrete sample (nominal value 125 mm)

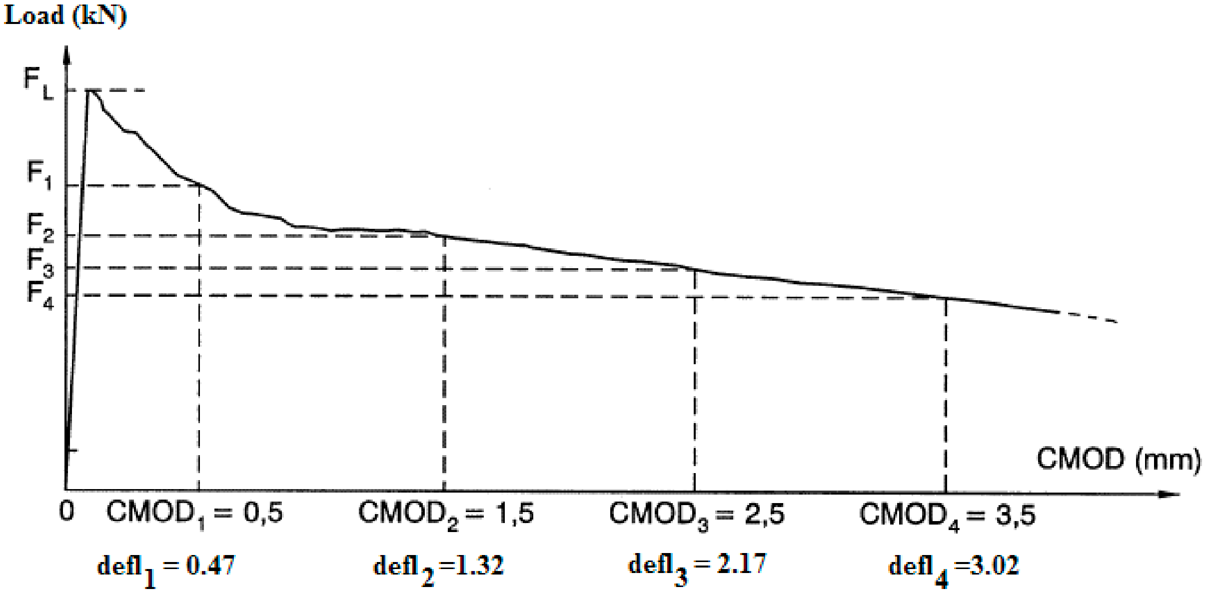

Figure 2. Load-deflection curve of test results.

Value ${}_{fR1}$ (CMOD = O.5 mm) is used for the Serviceability Limit State.
Value ${}_{fR3}$ (CMOD = 2.5 mm) is used for the Ultimate Limit State.

With the previous assumptions, FRC toughness can be classified by using two parameters: the first one is a number representing the fR1 class while the second one is a letter representing the ratio f_{R3k}/f_{R1k} .
The strength interval for fR1k is defined by two subsequent numbers in the series:
1.0; 1.5; 2.0; 2.5; 3.0; 4.0; 5.0; 6.0; 7.0; 8.0 [MPa]

The f_{R3k} / f_{R1k} ratio can be represented with letters a, b, c, d, e, corresponding to the ranges:
“a” if $0.5 \leq f_{R3k} / f_{R1k} \leq 0.7$
“b” if $0.7 \leq f_{R3k} / f_{R1k} \leq 0.9$
“c” if $0.9 \leq f_{R3k} / f_{R1k} \leq 1.1$
“d” if $1.1 \leq f_{R3k} / f_{R1k} \leq 1.3$
“e” if $1.3 \leq f_{R3k} / f_{R1k}$

Some practical indications can be given for the above mechanical properties, giving minimum performance levels:

- Compression: minimal early age strength (demolding, handling and storing) $f_{ck} > 15$ MPa; minimal strength at 28 days, $f_{ck} > 40$ MPa, strength at 90 days, $f_{ck} = 50$ MPa
- Flexion: minimal early age strength (demolding, handling and storing), $f_{R1k} > 1.5$ MPa, $f_{R3k} > 1.5$ MPa; minimal strength at 28 days, $f_{R1k} > 4$ MPa, $f_{R3k} > 4$ MPa; a typical minimum dosage for steel fibers is 40 kg/mc.

A typical minimum network recommended is 10 000 linear meter/ m^3.

By using the proposed classification, a material having, for example, the following classification:
FRC 40/50 - 5C
means:

- Compressive strength $f_{ck} = 40$ MPa
- Residual flexural strength at CMOD = 0.5 mm f_{R1k} 5N/mm^2
- Residual flexural strength at CMOD = 2.5 mm f_{R3k} 5N/mm^2

Since brittleness must be avoided in structural behavior, fiber reinforcement can be used as substitution (even partially) of conventional reinforcement (at ULS), only if both the following relationships are fulfilled:

$f_{R1k}/ f_{Lk} > 0.4$
$f_{R3k} / f_{R1k} > 0.5$

Where f_{Lk} is the characteristic value of the nominal strength, corresponding to the peak load (or the highest load value in the interval 0 – 0.05 mm), determined from the EN 14651 beam test.

When FRC is used as the main reinforcement, $f_{R1k} /f_{Lk} > 1$ is recommended.

It is recommended to realize 12 beams per dosage and concrete mix formula.

Bending tests

Three bending tests were performed with the loading set-up illustrated in Figure 3, in displacement control, by adopting a 1000 kN electromechanical jacket with PID control and by imposing a stroke speed of 10 µm/sec. The segments were placed on a cylindrical support with a span of x mm. The load, applied at midspan, was transversally distributed by using a steel beam as shown in Figure 3. During the test, the following measures were continuously registered:

- The load F, measured by means of a 1000 kN load cell with a precision of 0.2%
- The midspan displacement, measured by means of four potentiometer wire transducers placed along the transverse line
- The crack opening at midspan, measured by means of two LVDTs.

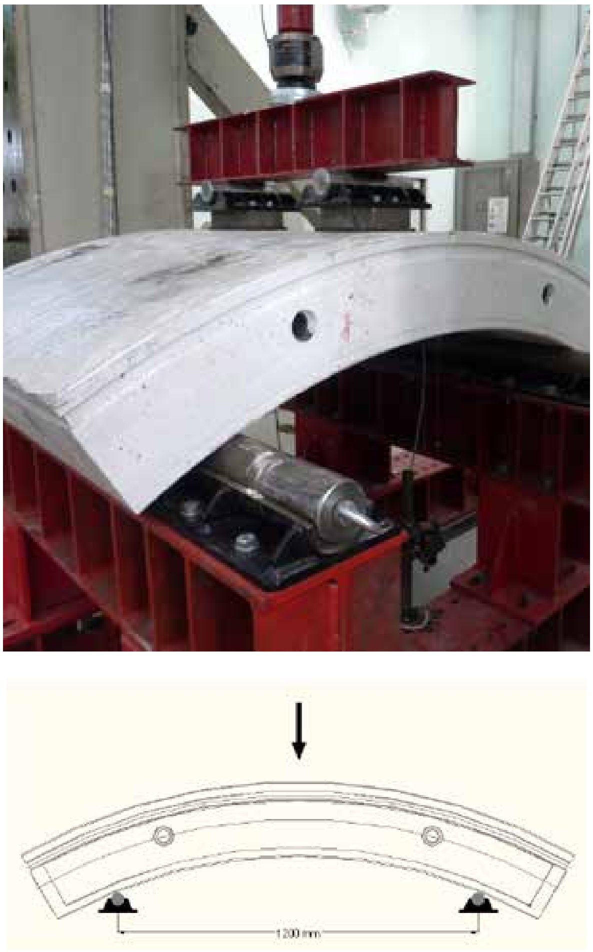

Figure 3. Bending test set-up.

Furthermore, the crack pattern was recorded at different stages with the help of a grid plotted on the intrados surface (100 x 100 mm).

Point load tests

Three point load tests were performed by applying two point loads at the segment and by adopting the same steel plates used by the TBM (Figure 4). A uniform support was used, as the segment was placed on a suitably designed stiff beam. Two 2000 kN rackets were used for every steel plate.

The load was continuously measured by pressure transducers. Four wire transducers (two located at the intrados and two at the extrados) measured the displacement of the shoes, while one LVDT transducer was applied between the load shoes to measure the crack openings.

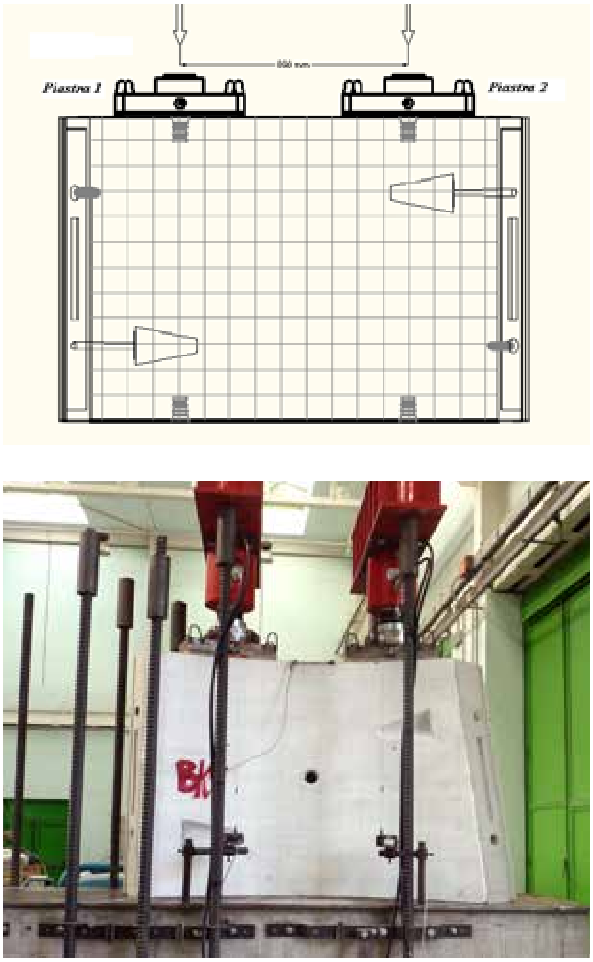

Figure 4. Point load test set-up.

CONCLUSION

Two different kinds of tests on segments should be performed: a test simulating the point loads effects on the segments, produced by the TBM machine during the digging phase and a flexural test simulating the behaviour of the segments when loaded under bending.
The combination of material property on beam tests, bending tests on segment, and point load tests on segment showed the effectiveness of the steel fibers in ensuring the required performance of FRC:

- hardening post-crack behavior at section level (beam test) allow immediately
    - Cracking control at SLS
    - Structural ductility (ULS)
- Multi-crack on bending
- Concentrated load: the presence of fibers controlled the crack opening <0.2 mm
- Performance class mini type C40/50 4 c

Through this approach, we confirmed that FRC combines economic advantages with good structural behavior. Nevertheless, to obtain the desired results it is worth noting the need to develop an accurate study of the material, i.e. the fiber typology suitable to a specific concrete matrix.

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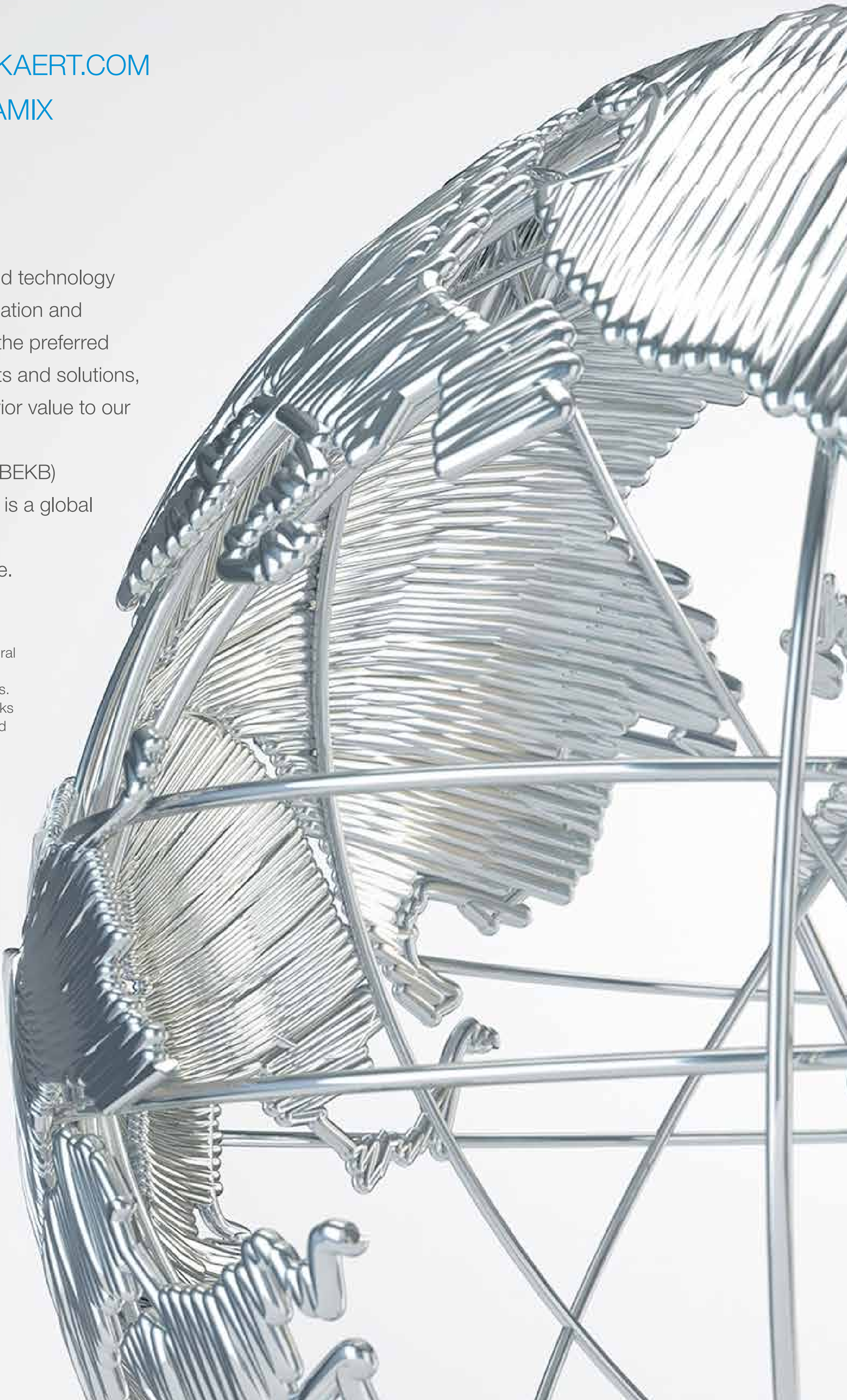

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