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CONCRETE LINTELS REINFORCED WITH STEEL FIBRES ORIENTED BY A MAGNETIC FIELD

Kristýna Carrera[a], Karel Künzel[b], Petr Konrád[a,*], Radoslav Sovják[a], Václav Papež[b], Michal Mára[a], Jindřich Fornůsek[a], Přemysl Kheml[a]

[a] *Czech Technical University in Prague, Faculty of Civil Engineering, Experimental Centre, Thákurova 7, 166 29 Prague 6, Czech Republic*

[b] *Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Electrotechnology, Technická 2, 166 27 Prague 6, Czech Republic*

[*] corresponding author: petr.konrad@fsv.cvut.cz

Abstract. This paper explores the possibility of applying the technique of magnetic orientation of steel fibres for manufacturing a concrete structural element of realistic dimensions, compared to small laboratory specimens. This technique could be a part of an answer to the current need for faster and automated production in the prefabrication industry. The examined specimens have dimensions of commonly used lintels in construction, 80 mm × 100 mm × 980 mm. The properties of specimens with magnetically oriented fibres are compared with same size specimens prefabricated conventionally. The orientation of fibres has been confirmed by Q-factor non-destructive testing method using a measuring coil. All specimens were tested with a four-point bending test. The specimens with oriented fibres show a significantly higher flexural strength, by 150 %, than specimens produced conventionally with the same volume of fibres.

Keywords: Magnetic, orientation, fibre, align, concrete, lintels, beams.

1. Introduction

During the production of cement, a large amount of CO_2 is produced, indirectly due to the energy consumption and directly because of the chemical reactions in the conversion of limestone to clinker [1]. With increasing demands to reduce the carbon footprint and speed up the production processes, new materials and technologies are being developed. However, another key aspect of the more sustainable use of cement is through manufacturing processes that result in significantly more efficient products. High-performance concrete (HPC) allows us to use less volume of the material to achieve the same required strengths while increasing the overall durability and longevity thanks to its resistance to the environment [2]. Fibre reinforcement also benefits from the use of HPC as a stronger fibre-matrix bond can be achieved for better efficiency [3].

This paper investigates the emerging technology for fibre orientation in fresh concrete using a magnetic field to manufacture a high-performance fibre-reinforced concrete (HPFRC). This increases the efficiency of the material even further, but the technology also has the potential to be fully automated in the future. One recent industry requirement is the speed and automation of production. Furthermore, the use of fibres specifically aligned as needed can present an alternative or replacement to conventional, labour-intensive steel-bar reinforcement. Although several authors have addressed the topic of magnetic orientation [4–9], none of them tested an element with realistic dimensions for a practical use in construction. In this paper, lintels of common dimensions were fabricated and experimentally tested.

Since the successful magnetic orientation is not immediately apparent, it must go hand in hand with a certain non-destructive evaluation that can confirm it. This is also a necessary step for a future automated industrial production, as quality control must be present. As part of the experimental campaign, a non-destructive method from previous studies [10] is also employed to test it with these larger specimens.

2. Materials and methods

2.1. Manufacturing of specimens

The mixture design of the HPFRC is in Table 1. It is used in combination with 1.5 % of volume of Weidacon FM high-strength steel fibres with a length of 13 mm and a diameter of 0.15 mm, which corresponds to an aspect ratio of 87. The mixture was prepared in a 50 l pan mixer. At first, all dry constituents were mixed for 3 minutes, then water with a high-range water-reducer (HRWR) was added and mixed for additional 10 minutes for the full activation of the used HRWR. Finally, steel fibres were sprinkled into the running mixer, to eliminate fibre clustering, which took 5 more minutes. The fresh HPFRC was poured by hand into the centres of plastic moulds to let the material flow into the whole volume (Figure 1). This ensured that all specimens were manufactured the same way.

Constituent	**Rel. weight**	**kg/m^3**
Cement 42.5 R	1.000	692.7
Water	0.281	194.5
Silica fume	0.110	76.2
Silica flour	0.280	194.0
High-range water-reducer	0.057	39.5
Silica sand 0/1.2 mm	0.820	568.0
Silica sand 0/4.0 mm	0.940	651.1

Table 1. The mixture design.

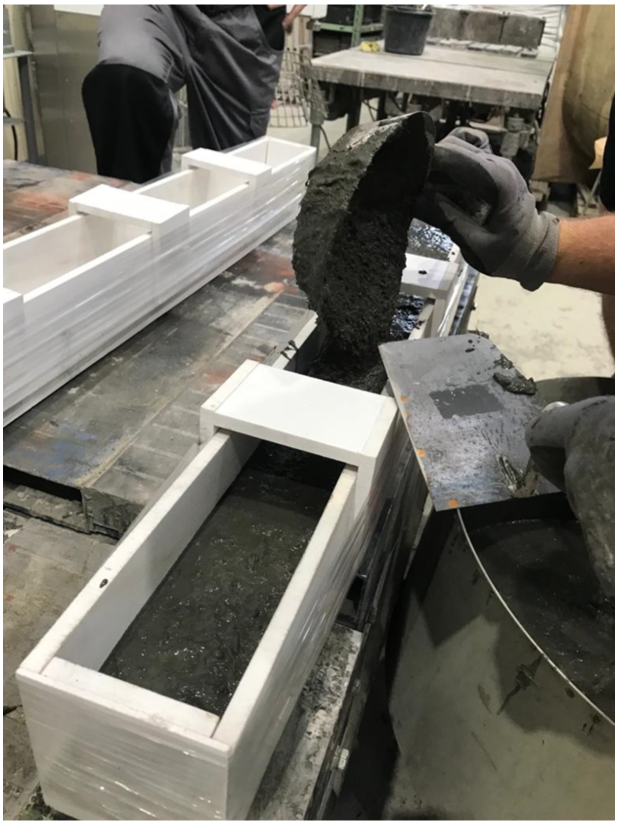

Figure 1. The filling of moulds.

The moulds had dimensions of 80 mm × 100 mm × 980 mm. These dimensions were chosen because of the typical dimensions of concrete lintels above doors. Plastic moulds were used instead of steel ones because the magnetic orientation process would otherwise be prevented by the steel enclosure. To ensure consistent results, one non-oriented and one oriented specimens were always made in sequence. The filled moulds were vibrated for 10 seconds.

The filled moulds intended for magnetic orientation were closed from the top and immediately subjected to the magnetic orientation process. It is important that relatively low manufacturing times are maintained as the fresh mixture needs to have suitable rheology so the magnetic field can overcome the matrix's resistance against the fibre rotation [11]. The fibres have been oriented with a special coil device

Figure 2. Device.

using a magnetic field (Figure 2). It consists of a coil generating the required magnetic field and a plastic conveyor. The same device has been used in a previous study [12], which is describing it in more detail. The device is capable of treating specimens with cross-sections up to 100 mm × 100 mm and the parameters are as follows. The coil has 215 turns of copper tube with a diameter of 6 mm/4 mm (outer/inner diameter) with cooling water circulating inside the coil winding. In total, 5 compensating capacitors are connected in parallel to the coil, each of them has a capacity of 300 µF. The voltage is 300 V and is provided by a step-down autotransformer connected to a 400 V mains line. The current passing through the inductor is 150 A and generates a magnetic induction of 100 mT.

Steel fibres interact with magnetic field and align themselves in direction of magnetic field lines, in our case along the longitudinal axis of the specimen. The orientation of the fibres is ensured by passing the specimens through the device. Specimens were pulled through manually at a slow speed, approximately 2 cm/s (Figure 3). A total of 11 specimens were produced, 6 of which with oriented fibres and 5 specimens produced in the standard way with fibres randomly oriented. The specimens were produced in three batches. First to test the manufacturing setup and the technology (moulds, their transport and passing through the device) for one reference and one oriented specimen and the next two batches included 2 oriented, 2 non-oriented and 3 oriented, 2 non-oriented, respectively.

Figure 3. Pulling a filled mould through the device.

Figure 4. An example of Q measuring process.

Figure 5. Four-point bending test setup.

2.2. Testing

Specimens were demoulded after 24 hours from mixing and measured non-destructively. The non-destructive method using a measuring coil with an inserted specimen is used for evaluating the fibre orientation. The parameter most sensitive to the quantity and orientation of the inserted fibres is the quality factor Q of the measuring coil, which is a dimensionless value calculated using the coil's resistance, inductance, and frequency of the passing electrical current. The quality factor Q and its use for this purpose is described more extensively in previous works [10, 13, 14]. The measurement setup consists of an impedance meter HIOKI IM3536 and a coil with 15 turns of a copper wire with a cross-section of 16 mm^2. The measuring coil has a diameter of 155 mm and a length of 105 mm (Figure 4). The measurement is time-independent and can be performed even with fresh concrete still inside the mould. The only material that affects the measurement is a magnetic material, which, in our case, are the steel fibres. If the fibres are aligned in the desired direction along the longitudinal axis of the specimen, i.e., parallel with the axis of the measuring coil, the fibres are interacting strongly with the measuring coil, leading to a low value of Q. Vice versa, specimens with randomly oriented fibres or perpendicularly to the axis of the measuring coil have a high value of Q. The measuring is performed on the frequency range from 1 MHz to 6 MHz, where Q shows the highest sensitivity for this particular setup. The peak Q value is used for a comparison between the specimens. The measurement is comparative and the absolute value is dependent not just on the orientation of the fibres but also on the size of the specimen (the volume of the fibres) and the measuring coil's parameters. Only specimens with the same percentage of fibre volume can be compared with each other [10]. All specimens were measured at 200 mm, 400 mm, 500 mm, 600 mm and 800 mm from one end.

After the non-destructive measurement, the specimens were kept for 27 days in a dry room environment at 20 °C. After this time period, they were tested using a four-point bending experiment. The test was done using a hydraulic loading machine with a deformation control of 0.1 mm/min. The total span was 900 mm and the loading points were 300 mm apart in the centre of the span. Two displacement sensors on the sides of the beam measured the displacement which was then averaged. All specimens were tested until a complete specimen failure. The complete setup is shown in Figure 5. The broken halves were then subjected to compressive strength tests with a loading area of 80 mm × 100 mm.

3. Results

Figure 6 shows the measured quality factor Q of the first two manufactured specimens of the first batch (oriented – S, non-oriented – N, same designation for next graphs). The measuring was performed at different points along the specimen, which is indicated on the x-axis. A lower value of Q means more aligned fibres in the direction of the measuring coil's axis or lower fibre volume. This data shows that the oriented specimen have similar values of Q at all points. The difference between the largest and smallest values relative to the mean value for the individual measurements ranges from 3 % to 12 %, unlike the non-oriented specimen, where the Q values are highly

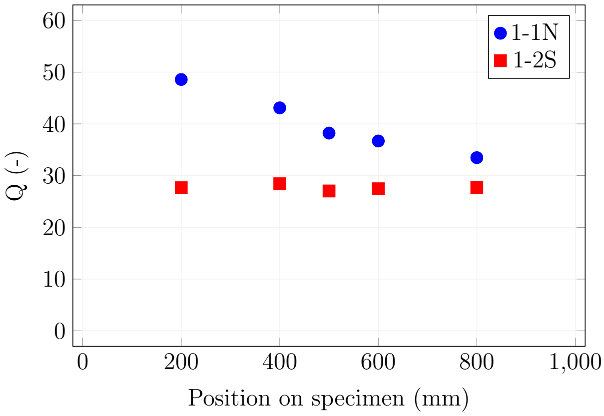

Figure 6. Q for the first batch of specimens.

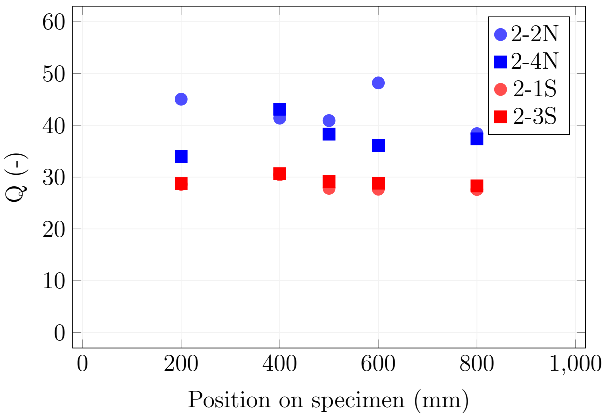

Figure 7. Q for the second batch of specimens.

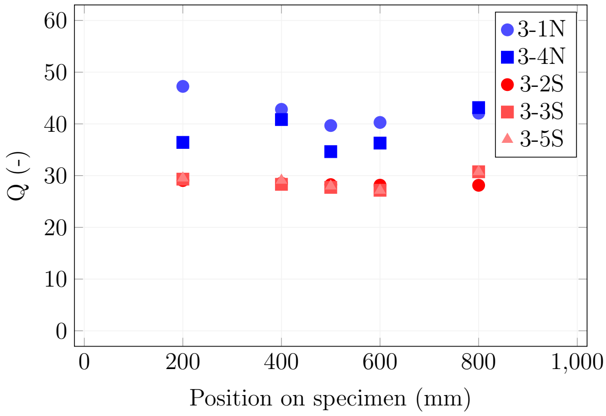

Figure 8. Q for the third batch of specimens.

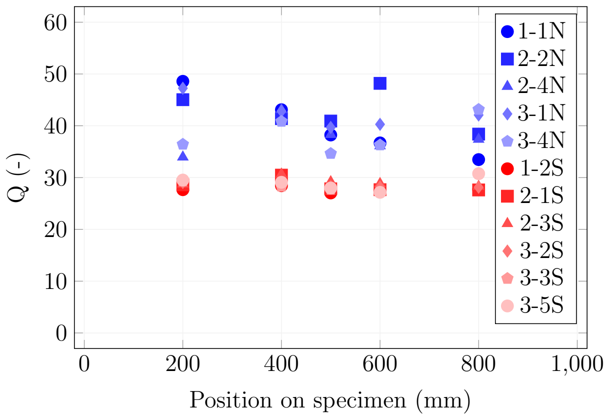

Figure 9. Summary of all Q measurements.

variable, from 18 % to 38 %. Since both specimens have the same fibre volume, the difference of Q is caused by the different orientation of fibres in the measured cross-sections. In each measured point of the oriented specimen, Q values are lower than at any point of the non-oriented specimen. This means that in each measured point, the oriented specimen has more aligned fibres in the preferred direction than the non-oriented specimen. The measurements of the first batch were carried out twice. The first measuring is identical to the second measuring which confirms the functionality and reliability of the measuring method.

Figures 7 and 8 show the second and third batches, respectively. All results of the non-destructive measurement are summarised in Figure 9. The overall average value of Q for specimens exposed to a magnetic field is 29.15. Meanwhile, reference specimens have an average Q of 38.35, which is 23 % higher than the oriented specimens. All of the oriented specimens also have lower spreads of Q.

All of the measured results are summarised in Table 2. The load-displacement diagrams obtained from the bending experiments are shown in Figure 10. From the graph and from the flexural strength values, it is clear, that the specimens treated with the magnetic field performed significantly better. For the subsequent comparison of the mechanical parameters, the outlying values were excluded (specimens 2-4N and 3-2S). The average flexural strength of oriented specimens is 15.93 MPa and 7.20 MPa for non-oriented specimens, which is an increase of 121 %. We can also compare the dissipated mechanical energy, which is calculated as the area under the load-displacement curve. In this case, the average values rose by 178 % for oriented specimens. However, we can observe, from Figure 10 that the peak loads were achieved for larger displacements for the oriented specimens, i.e., the orientation improved the deflection hardening behaviour. The energy-absorbing capacity until the maximum peak is then much higher, although the force after it decays faster to similar values as for the non-oriented specimens, which is the result of the fibre length. Generally, the higher capacity to dissipate mechanical energy would be beneficial in the case of impact loading. The compressive strength has been affected minimally. The average compressive strength of oriented specimens is 128 MPa and 118 MPa for non-oriented specimens, which is a relative difference of 9 %.

In line with a previous study [10], the non-destructive measuring of Q correlates well with flexural strengths (Figure 11). The specimens with a higher flexural strength and higher dissipated energy have

Specimen	Flexural strength [MPa]	Quality factor [−]	Dissipated energy [J]	Compressive strength [MPa]
1-1N	7.55	38.22	79.05	120.19
1-2S	18.34	27.03	194.65	134.06
2-1S	13.91	27.83	100.09	126.19
2-2N	6.69	40.91	44.13	113.88
2-3S	13.95	29.18	103.96	116.56
2-4N	3.88	38.30	18.44	110.63
3-1N	6.87	39.68	39.20	125.25
3-2S	22.12	28.26	173.85	126.19
3-3S	17.17	34.64	115.05	131.50
3-4N	7.68	34.64	54.12	118.31
3-5S	16.29	27.98	97.63	132.63

Table 2. Summary of the results.

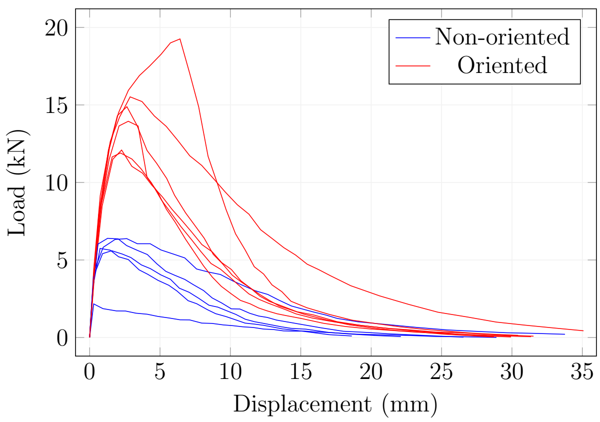

Figure 10. Load-displacement diagrams.

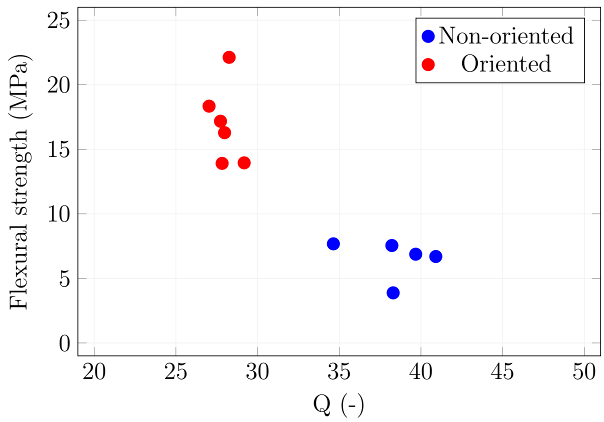

Figure 11. The quality factors Q compared to the measured flexural strengths for all specimens

a lower value of Q and vice versa. This is described in more detail in a previous study [10].

Figure 12 shows an example of three damaged specimens during the bending experiment together with the values of Q. As mentioned earlier, a higher Q means lower fibre volume of fewer preferentially-oriented fibres. At this stage, the non-destructive technique cannot differentiate between the two cases and it is a topic for future research. Nevertheless, both cases present a weak point for the element. It was expected that at these points, the failure would occur, but this assumption was generally not met. In these examples, only in the case of the specimen 2S, the failure initiated in the constant moment region, although at the point of lower Q. Other specimens developed the main crack at various locations with various Q values. It is worth noting, that the non-destructive measurement cannot predict the homogeneity of the matrix or, for example, the fibre anchoring strength or fibre interactions, which would be the key parameters determining the behaviour of the examined volume. Also, for the oriented specimens, as was seen in the previous graphs, the differences in Q are rather low.

Compared to a study with small-scale specimens [12], the mechanical parameters of the lintels showed a higher spread. It was assumed that, as the non-destructive measurement suggests, the magnetic orientation manufacturing also creates more homogeneous material and, therefore, lowers the spread of flexural strengths, dissipated energies, and other characteristics. From the graph in Figure 10, we can clearly see that this is not the case. This only highlights the necessity for experimental campaigns with larger-scale production, to provide a better picture regarding the scalability of all steps of new manufacturing techniques.

4. Conclusions

In this paper, the technology of magnetically oriented fibres has been tested on lintels with more realistic dimensions. Thanks to the exposure of the fresh concrete with steel fibres to a magnetic field inside

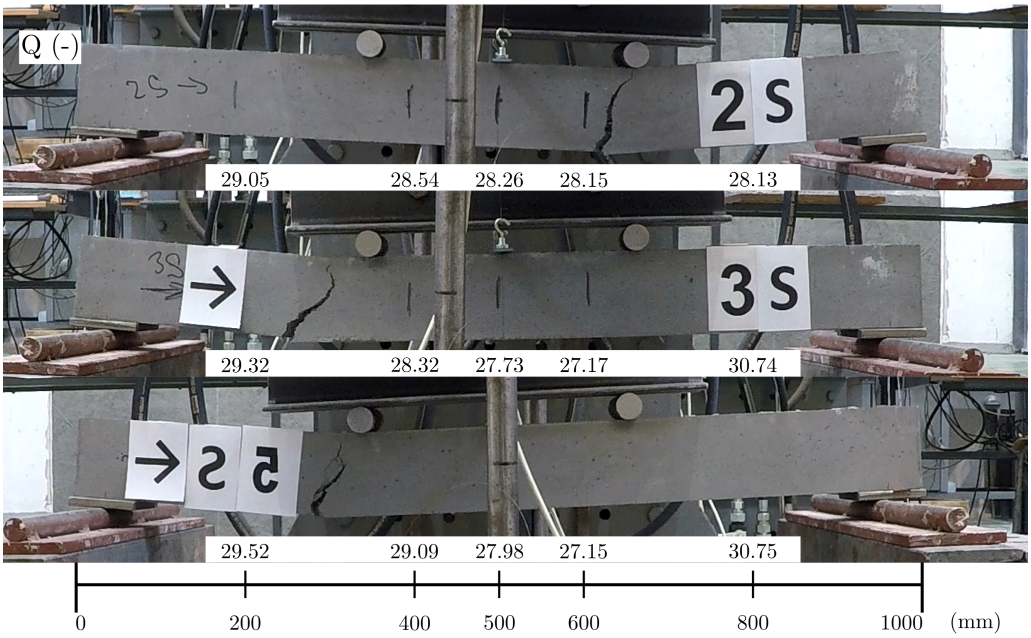

Figure 12. Cracking patterns compared with the non-destructive measurement results.

the orienting device, we can significantly improve the mechanical parameters in comparison to the reference specimens produced in a conventional way.

- Flexural strength is increased by 121 %.
- Dissipated energy is increased by 179 %.
- Compressive strength is increased by 9 %.
- The non-destructive measurements confirmed stable results along the specimen.
- The quality factor Q of oriented specimens is, on average, 24 % lower than for non-oriented specimens.

The results confirm the stability and repeatability of the technology to eventually replace the conventional steel bar reinforcement.

Acknowledgements

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