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A proposed pendulum impact test method for UHPFRC

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Abstract

The present study aims to develop a pendulum impact test method to determine the impact resistance of Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC). Different impact test methods were investigated, and their shortcomings were identified. These shortcomings include, but are not limited to, energy absorbed by the test instrument and inertial effects of the test specimen. The proposed test method has been designed to address these shortcomings in determining the impact resistance of UHPFRC. Measuring equipment was used to further extend the capabilities of the test method. An accelerometer was used to record an acceleration time-history of the impact event at 96 kHz. Furthermore, high-speed photography (7 600 fps) was used for motion tracking and Digital Image Correlation (DIC).

Keywords: Impact resistance, Loading rate, Pendulum impact, Test method, UHPFRC

1. INTRODUCTION AND BACKGROUND

Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC) is known for its enhanced mechanical properties [1] and is therefore considered a potential option for the construction of structures subjected to severe loading conditions such as vehicular impacts due to its ability to absorb energy and remain ductile [1]. Despite this and the fact that it has long been known that concrete is a strain-rate sensitive material [2], the dynamic mechanical properties of UHPFRC is not yet well understood [2]. This stems from a lack of standardised test methods [2] which hinders the progress in understanding the dynamic mechanical properties of UHPFRC. It is therefore important to develop relevant test methods that enable standardisation and promote research progress.

Existing test methods developed to test materials at different strain rates are shown in Figure 1, along with their strain rate ranges and associated real-life applications. Different test methods are used to apply rapid loads (impacts) to test specimens. These methods include the use of gravity through drop-weight and pendulum impact tests, hydraulic machines and stress waves using the Split-Hopkinson Pressure Bar (SHPB).

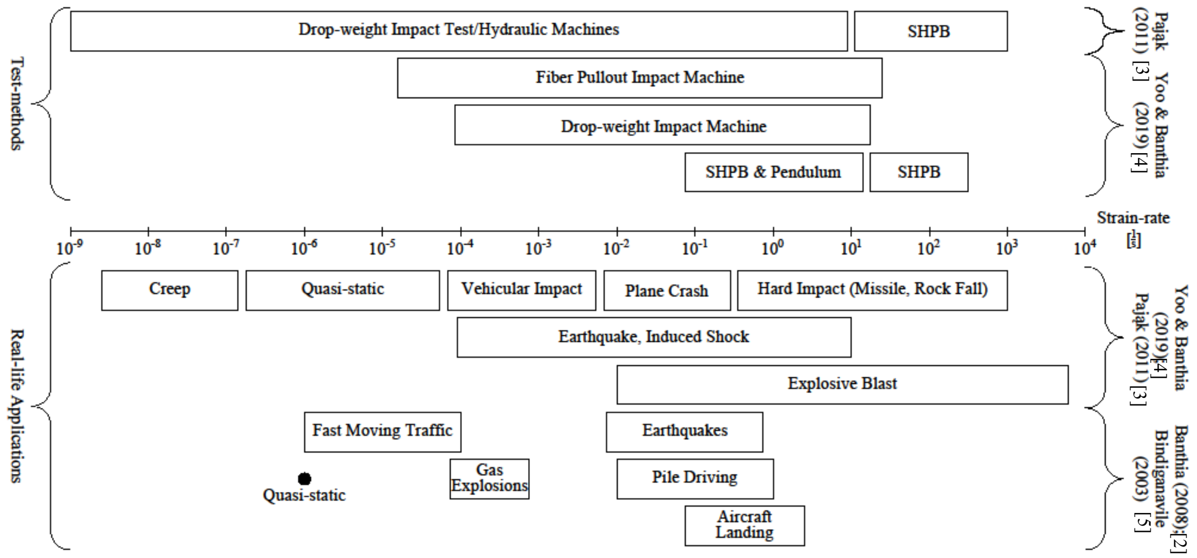

Figure 1: Strain rates of impact testing methods and their associated real-life applications (adapted from [6])

The drop-weight impact test method is the most common impact test method and makes use of a free-falling mass to rapidly apply a load to a test specimen. A comparison of the number of drops required to attain a predetermined failure criterion can be used to interpret the data. It is also possible to install instrumentation on the mass, test specimen, and supports [10, 11]. The rate of load application is directly proportional to the height from which the mass is allowed to fall.

The advantages of this test method are attributed to its simplicity, which facilitates its implementation and makes it less expensive than other testing methods [7]. ACI Committee 544 has recognized the drop-weight impact test method described in ACI 544.2R-89 as a standardized test method for the impact testing of Fibre-Reinforced Concrete (FRC) [8]. However, the simplicity of the test method introduces some limitations, the primary being the rebound effect, which generates a secondary impact when the test specimen does not fail under the initial impact [13, 14]. Without instrumentation, the additional load caused by the secondary impact cannot be measured. Furthermore, when failure of the test specimen occurs it is difficult to determine the amount of energy absorbed by the test specimen without instrumentation, since the free-falling weight retains residual energy after impact. Furthermore, Abid et al. [7] found that a minimum of 55 test specimens are required for the ACI 544-2R test procedure to gain a 90 % level of confidence in the test results. Finally, the ACI 544-2R test procedure is not practically suited for testing FRC and UHPFRC since an excess of 1 000 blows may be needed for a test specimen to reach the "first-crack" [9] or failure criteria [7, 9, 12]. Ramakrishnan et al. [9] discarded further attempts to test fibre-reinforced shotcrete test specimens (thickness of 76 mm) until failure due to the large number of blows needed to reach the "first-crack" criteria. Other limitations include the influence of boundary conditions and inertial resistance of the test specimen which may lead to over-estimations of the impact resistance [10].

Another common impact test method is the pendulum impact test method which involves a weighted hammer attached to an arm that moves in a circular motion prior to striking the test specimen. Similar to the drop-weight impact test method, the rate of load application is directly proportional to the height from which the mass is allowed to fall. Although this test method was originally intended for testing metals, several authors have successfully used modified versions of these tests on concrete [13-16, 17, 18]. The test method is versatile since different configurations may be used to test different mechanical properties of concrete such as flexural strength (beams [13-15] and plates[16]), direct tensile strength [17] and fibre pull-out strength [18]. The data obtained from this test method can be interpreted by similar means as the drop-weight impact test method and also allows for the use of instrumentation [13-16, 17, 18]. The pendulum impact test offers significant benefits such as eliminating the rebound effect [13, 14, 16], providing easy instrumentation [13, 18] and allowing adjustments to the impact energy and sample geometry. Despite these advantages, the main limitation of the pendulum impact test method is to consider the influences of boundary conditions and inertial resistance of the test specimen as to not over-estimate the impact resistance [13, 17, 18]. A futher limitation is the energy absorbed by the test instrument caused by the difference in stiffness between the test instrument and test specimen [15, 19]. Bluhm [19] argued that the pendulum should be sufficiently stiff in order to reduce the elastic energy stored in the pendulum. Gopalaratnam et al. [15] further suggested that the adverse effects of test specimen inertia may be limited by ensuring a large difference in mass between the pendulum and test specimen in conjunction with a large difference in stiffness. These limitations, however, are applicable to all impact test methods and not only the pendulum impact test method.

Other impact test methods include the projectile impact test method [20] (of which the limiting factors are safety and the need of equipment able to achieve very high data sampling rates), impact testing by means of servo-hydraulic machines [6] (of which the main limiting factor is the cost of the machine), the SHPB impact test method (which has several limitations such as test specimen size [13], the lateral inertial confinement effect [21] and boundary conditions [22]) and the fibre pull-out test method, where no correlation between a single-fibre pull-out test and beams tested under impact loads could be found. This has been attributed to the fact that a single-fibre pull-out test does not consider fibre orientation, nor fibre-to-fibre interaction [4].

In summary, the main limitations that adversely affect all impact test methods are test setup stiffness and test specimen inertia. Other limitations are test repeatability and reliability, cost, safety and practical applicability. The main objective of this study is to propose a pendulum impact test method that has been purposely designed to take into account these limitations. A direct comparison has been made between the proposed pendulum impact test method and the drop-weight impact test method specified in ACI 544.2R-89. This is due to the gravity-driven nature of both the test methods and similarities in their application. Both test methods apply a similar range of kinetic energy at similar impact velocities. It is important to note that the strain rate experienced by a test specimen is directly proportional to the impact velocity. Therefore, it would be unfair to compare these two test methods to other test methods such as the projectile impact test method.

2. DESIGN AND SETUP OF THE PROPOSED PENDULUM IMPACT TEST DEVICE

The setup of the proposed pendulum impact device is shown in Figure 2. The overall setup of the device and position of the high-speed cameras are shown in Figure 2 (a). Figure 2 (b) shows the setup and alignment of the test specimen perpendicular to the pendulum impact hammer, whereas Figure 2 (c) indicates the position of the accelerometer on the back end of the impact hammer.The pendulum arm consists of a 2 m piece of IPE 100 that rotates about two pillow block bearings attached to a frame connected to a 500 mm thick reinforced concrete wall. Additional plates were added at the bottom of the pendulum arm so that the total mass of the arm equals 50 kg. The plates were configured such that the centre of mass of the pendulum arm is aligned with the tup. This is to avoid introducing additional moments to the test specimen during impact.

The test specimen is supported at the ends by adjustable brackets attached with thin wires to the overhead frame. This assembly has a mass of approximately 3 kg, resulting in a pendulum arm to test specimen ratio of 16.67. By performing modal analyses of the test specimen support assembly it was found that the natural frequency of the assembly was reduced by a factor of 2.14 due to the mass of the brackets at the ends of the test specimen and due to the test specimen hanging from wires when compared to a test specimen that is traditionally simply supported. From the dynamic calculations performed by Gopalaratnam et al. [15], a reduction of the natural frequency of the test specimen results in an increase in the ratio of stiffness between the pendulum and test specimen for a constant pendulum stiffness. From the calculations it can further be deduced that the stiffness ratio has a larger influence on the over-estimation of the impact resistance of the test specimen. Therefore, it is expected that more reliable results may be obtained during testing since the pendulum is expected to store less elastic energy and the test specimen is expected to give less inertial resistance.

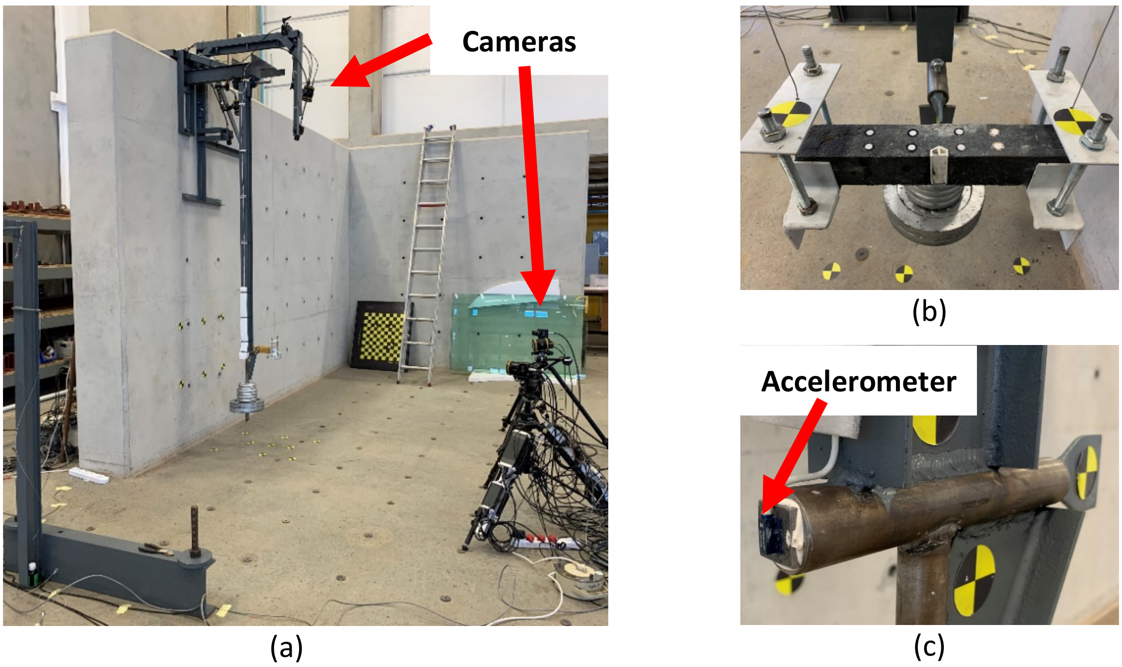

Figure 2: Setup of the proposed pendulum impact test device

3. EXPERIMENTAL PROGRAM AND TEST RESULTS

3.1 Mixture Design and Quasi-Static Mechanical Properties

The mixture of UHPFRC considered for the study is shown in Table 1. The table also displays the Relative Densities (RD) of the materials. The materials used were a CEM I 52.5R, undensified silica fume (USF), unclassified fly ash (FA), water, Dolomite stone (≤ 9.50 mm), Dolomite sand (≤ 4.75 mm), a superplasticiser and 2 % (by volume) hook-ended steel fibres. The steel fibres had a length of 30 mm and diameter of 0.50 mm and a tensile strength of 1 500 MPa. A total of ten 100 mm cubic test specimens were cast to determine the compressive strengths of the mixture in accordance with SANS 5863:2006. Three 200 mm x Ø100 mm cylindrical test specimens were cast to determine the modulus of elasticity and Poisson's ratio in accordance with ASTM C469. The cylindrical test specimens were cut in half in order to determine the splitting tensile strength in accordance with SANS 6253:2006. Lastly, three beams of 500 x 100 x 100 mm in dimension were cast to determine the modulus of rupture in accordance with SANS 5864:2006. The mean values of the quasi-static mechanical properties are shown in Table 2.

3.2 Proposed Pendulum Impact Test Method Results

Figure 3 displays the results of the impact tests performed at various fall heights. From the figure it can be seen that an exponential decrease in the number of blows were needed for the test specimen to reach failure with an increase in the fall height. A p-value test was performed on the pearson product-moment correlation coefficient between the fall height and the logarithm of the number of blows. A p-value of less than 0.05 was achieved and therefore the results were deemed to be statistically significant. Merely four test specimens were required per fall height (which resulted in 16 test specimens in total) required to obtain statistically significant data as opposed to the 55 test specimens required as proposed by Abid et al. [7]. Furthermore, it is clear from the figure that significantly less blows were needed for the test specimen to reach failure as opposed to that of the ACI 544.2R-89 drop-weight impact test. The proposed pendulum impact test method required a maximum of 30 blows for the test specimen to reach failure at the lowest fall height as opposed more than 1 000 blows required by the ACI 544.2R-89 drop-weight impact test. It can also be seen that with an increase in fall height, a decrease in dispersion of the results occurred.

Figure 4 shows an example of the acceleration time-history of an impact event obtained by the accelerometer placed on the proposed pendulum impact test device. The acceleration time-history of an impact event may be analysed by means of Fast-Fourier Transformation (FFT), Response Spectrum Analysis (RSA), or by generating an Euler characteristic curve followed by a Principal Component (PC) analysis in order to distinguish between different impact events or to determine the associated strain rates and energy absorbed by the test specimen.

Figure 5 displays the capabilities of using high-speed photography. Capturing images at 7 600 fps enables detailed observations to be performed as can be seen in Figure 5 (a). With the use of software such as TEMA [23] it is possible to perform motion analyses and Digital Image Correlation (DIC). From Figure 5 (a) it can be seen that the movement of the test specimen during the impact event can be accurately tracked, which gives rise to a multitude of calculation possibilities such as calculating deflections, rate of change of deflection, rotation of the test specimen about it's supports, etc. This can further be extended with DIC which allows for the calculation of strains and therefore strain rate. From Figure 5 (b) it can be seen how the change in strain in the test specimen occurred during the impact event. The blue colour indicates a strain of approximately zero whereas the red indicates tension. As soon as the tup of the pendulum makes contact with the test specimen it can be seen that a tension zone develops at the opposite side of the test specimen.

Table 1: Mixture design

Material	**RD**	**Mixture [kg/m^3]**
CEM I 52.5R	3.14	542
Undensified silica fume	2.45	146
Unclassified fly ash	2.22	146
Water	1.00	146
Dolomite stone ≤ 9.50 mm	2.85	251
Dolomite sand ≤ 4.75 mm	2.91	1 240
Superplasticiser	1.06	25.6
Hook-ended steel fibres	7.85	149
Theoretical density		2 646

Table 2: Quasi-static mechanical properties

Property	**No.**	**Mean**
Compressive strength [MPa]	10	167.8
Modulus of elasticity [GPa]	3	54.6
Poisson's ratio	3	0.146
Splitting tensile strength [MPa]	6	15.2
Modulus of rupture [MPa]	3	20.1

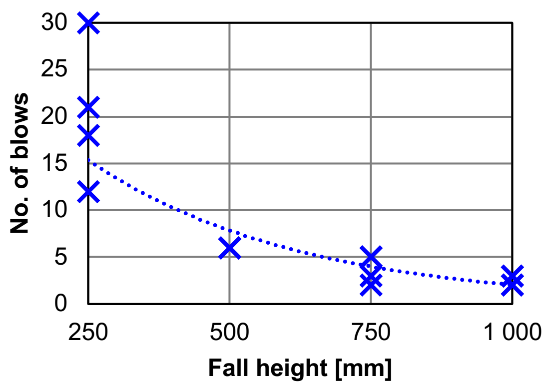

Figure 3: Number of blows required to reach failure at each fall height

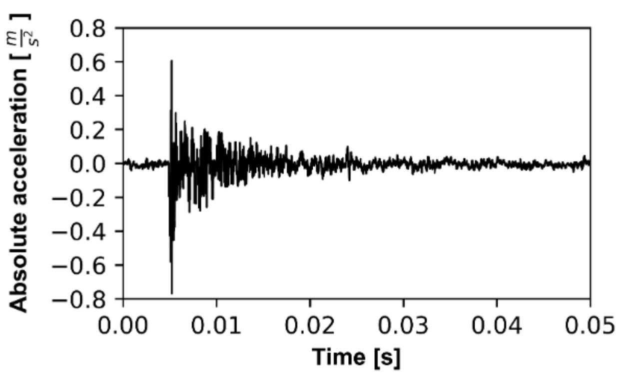

Figure 4: Acceleration time-history of an impact event

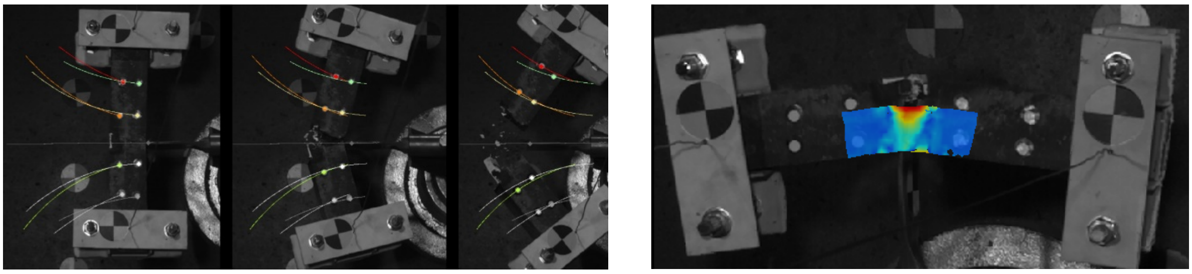
(a) (b)

Figure 5: Capabilities of high-speed photography

4. CONCLUSIONS AND RECOMMENDATIONS

From the test results it can be confirmed that the design and setup of the proposed pendulum impact test method has sufficiently addressed the following limitations:

- By changing the boundary conditions of the test specimen, the stiffness ratio between the pendulum and test specimen was increased, resulting in a decrease in inertial resistance of the test specimen and reducing the energy absorbed by the pendulum.
- Significantly less number of blows was needed for the test specimens to reach failure as opposed to the ACI 544.2R-89 drop-weight impact test.
- Significantly fewer test specimens need to be tested to obtain statistically significant test results as opposed to the ACI 544.2R-89 drop-weight impact test.
- The proposed pendulum impact test method does not suffer from the rebound effect.
- The proposed pendulum impact test method can easily be instrumented and adjusted or modified and is therefore more versatile than the ACI 544.2R-89 drop-weight impact test.

It is, however, recommended that tests should be conducted on UHPFRC mixtures that have different volumes of steel fibres in order to ensure that the proposed test method is able to differentiate between the mixtures. It is further recommended that the data obtained from the accelerometer and high-speed photography be properly analysed and compared to verify that they are able to produce reliable and reproduceable results that correspond with one another.

REFERENCES

[1] Othman, H., Marzouk, H. & Sherif, M., "Effects of variations in compressive strength and fibre content on dynamic properties of ultra-high performance fibre-reinforced concrete" *Construction and Building Materials* **195** (2019) 547-556.

[2] Banthia, N., "Enhancing impact and blast resistance of concrete with fiber reinforcement", in "Resilience of Cities to Terrorists and Other Threats", NATO Science for Peace and Security Series C: Environmental Security, North Atlantic Treaty Organisation, Moscow, 2008, 171-187.

[3] Pająk, M., "Dynamic response of SFRC under different strain rates – An overview of test results", in "7th International Conference, Analytical models and new concepts in concrete and masonry structures", AMCM2011, Kraków, 2011.

[4] Yoo, D-Y. & Banthia, N., "Impact resistance of fiber-reinforced concrete – A review", *Cement and Concrete Composites* **104** (2019) 103389.

[5] Bindiganavile, V., "Dynamic Fracture Toughness of FRC", PhD Thesis, The University of British Columbia, Canada, 2003.
[6] Adendorff, J., "A constitutive model for the dynamic tensile behaviour of UHPFRC", Masters' Dissertation, University of Pretoria, South Africa, 2002.
[7] Abid, S., Hussein, M., Ali, S. & Kazem, A., "Suggested modified testing techniques to the ACI 544-R repeated drop-weight impact test", *Construction and Building Materials*, **244** (2020) 118321.
[8] American Concrete Institute, *ACI 544.2R-89, "*Measurement of Properties of Fiber Reinforced Concrete", ACI Committee 544, USA, 1999.
[9] Ramakrishnan, V., Coyle, W., Dahl, L. & Schrader, E., "A comparative evaluation of fiber shotcretes", *Concrete International*, **3** (1981) 59-69.
[10] Suaris, W. & Shah, S., "Inertial effects in the instrumented impact testing of cementitious composites" *Cement, Concrete, and Aggregates*, **3** (1982) 77-83.
[11] Banthia, N., Mindess, S. & Bentur, A., "Impact behaviour of concrete beams" *Materials and Structures*, **20** (1987) 293-302.
[12] Al-Abdalay, N., Zeini, H. & Kubba, H., "Effect of impact load on SIFCON" *Global Journal of Researches in Engineering*, **19** (2019) 17-27.
[13] Máca, P., Sovják, R. & Konvalinka, P., "Impact testing of concrete: the measurement device", in "International Conference on Advances in Civil, Structural and Mechanical Engineering – CSME 2014", Institute of Research, Engineers and Doctors, Hong Kong, 2014, 63-67.
[14] Li, P. & Yu, Q., "Responses and post-impact properties of ultra-high performance fibre reinforced concrete under pendulum impact" *Composite Structures*, **208** (2019) 806-815.
[15] Gopalaratnam, V., Shah, S. & John, R., "A modified instrumented charpy test for cement-based composites" *Experimental Mechanics*, **24** (1984) 102-111.
[16] Yu, R., van Beers, L., Spiesz, P. & Brouwers, H., "Impact resistance of a sustainable Ultra-High Performance Concrete (UHPC) under pendulum impact loadings" *Construction and Building Materials*, **107** (2016) 203-215.
[17] Banthia, N., Mindess, S. & Trottier, J-F., "Impact resistance of steel fiber reinforced concrete" *ACI Materials Journal*, **93** (1996) 472-479.
[18] Pacios, A., Ouyang, C. & Shah, S., "Rate effect on interfacial response between fibres and matrix" *Materials and Structures*, **28** (1995) 83-91.
[19] Bluhm, J., "The influence of pendulum flexibilities on impact energy measurements", in "STP 176-EB Symposium on Impact Testing", ASTM International, West Conshohocken, 1956, 84-93.
[20] Adendorff, J. & Kearsley, E., "The influence of fibre reinforcement on the ballistic resistance of concrete", in "Proceedings of the Young Concrete Researchers, Engineers & Technologist Symposium", Johannesburg, South Africa, 2021, 132-139.
[21] Lv, T., Chen, X. & Chen, G., "Analysis on the waveform features of the split Hopkinson pressure bar tests of plain concrete specimen" *International Journal of Impact Engineering*, **103** (2017) 107-123.
[22] Ren, L., Yu, X., Guo, Z. & Xiao, L., "Numerical investigation of the dynamic increase factor of ultra-high performance concrete based on SHPB technology", *Construction and Building Materials*, **325** (2022) 126756.
[23] *Tema Pro – advanced motion and deformation analysis: ISAB (2022) Image Systems – TEMA and TrackEye, motion analysis*. Available at: https://imagesystems.se/tema-pro/ (Accessed: 3 March, 2023).