Visualization and analysis of concrete specimens damage after fire and blast experiments

R Štefan and M Foglar
Czech Technical University in Prague, Faculty of Civil Engineering, Department of Concrete and Masonry Structures, Thákurova 7, 166 29 Prague, Czech Republic
E-mail: radek.stefan@fsv.cvut.cz

Abstract. The paper is focused on visualization and analysis of concrete specimen damage after fire and blast experiments. A data visualization tool, based on an in-house MATLAB code, is described and its applicability and versatility are illustrated. In the first illustrative example, concrete spalling of fire exposed floor slab panels made of various types of concrete (without fibres, with polypropylene fibres, with steel fibres) is analysed. In the second example, the results of ultrasonic pulse velocity measurements of concrete bridge decks before and after blast experiments are shown in order to investigate the blast resistance of the decks made of different types of materials and to illustrate the damage of the decks in the form of the material degradation, surface spalling and puncture. The developed data visualization tool has been included in a freely available scientific computer program with a graphical user interface.

1. Introduction
Within an experimental investigation of concrete specimens subjected to fire or blast, data visualization is one of the methods that can be used for illustration of the measured results, their interpretation and subsequent analysis, both qualitative and quantitative – in connection with usual data analysis and descriptive statistical techniques. The data visualization approach has been employed by many researchers in order to display and analyse the amount of concrete spalling of fire exposed concrete specimens, e.g. [1–12]. The data (spalling depths, surface profile) can be obtained by manual measurements (e.g. by a depth slide gauge or by geodetic instruments) in a regular grid, e.g. [1–7], or by advanced photogrammetry, image processing, and 3D scanning methods, e.g. [11,12]. The data can be displayed in the form of contour plots – so called “spalling maps”, or other types of graphs, e.g. a surface plot. These figures provide information both about the spalling area and the spalling depths. Moreover, they can be used for descriptive statistical analysis in order to quantify the extent of spalling – e.g. by analysing the spalling area, volume, and depth, see e.g. [1–12].

The data visualization is also used in the diagnostics of structures by ultrasonic pulse velocity (UPV) measurements. Based on the pulse velocity, the material properties of concrete as well as its heterogeneity and damage (after fire, blast, etc.) can be assessed [13,14].

Although many data visualization software tools, both commercial and scientific, are currently available, see the above references, we decided to develop our own tool in MATLAB [15] environment, based on the experience that we have gained during our research in the field of fire and blast test of concrete structures. This tool is described in this paper.
2. Data visualization procedure

The data visualization tool has been developed in MATLAB [15] environment. The entire procedure implemented in the code is described in algorithm 1.

**Algorithm 1** Data visualization procedure implemented in the presented software tool

1: input a .xlsx file containing the measured data and the corresponding coordinates
2: set the geometry and dimensions of the analysed area
3: set the interpolation and extrapolation method
4: perform the interpolation and extrapolation
5: perform the statistical analysis
6: display the results in the form of contour plots or other types of graphs
7: export the figures

The individual steps of algorithm 1 are described below.

In **step 1**, an input .xlsx file is imported. The file contains both the measured data (e.g. the spalling depths, the UPV results, etc.) and the corresponding coordinates of the measurement points (their positions in the analysed area). In our approach, the data are obtained by manual measurements in a regular grid, see the examples described in sections 3 and 4.

In **step 2**, the analysed area of the specimen surface is defined by its geometry and dimensions.

In **step 3**, the method of interpolation and extrapolation of the data is specified. We use the built-in MATLAB function `scatteredInterpolant`, with the methods of interpolation: linear, nearest, or natural, and extrapolation: linear, nearest, or none, see the MATLAB [15] Documentation.

The interpolated and extrapolated data are obtained in **step 4** by MATLAB [15] `scatteredInterpolant` function.

A descriptive statistical approach can be employed in **step 5** in order to analyse the measured data (spalling depth, area, volume, UPV results, etc.) by usual statistical techniques (minimum, maximum, mean value, standard deviation, etc.).

In **step 6**, the results can be displayed in the form of contour plots (“maps” with isolines or isoareas) or other types of graphs (e.g. 3D surface plots, line graphs for selected sections of the specimen, etc.). The results of the statistical analysis can be displayed in a figure or exported separately in a text file or a .xlsx file.

In **step 7**, the created figure can be saved to a required format, such as .eps, .emf, .jpg, .pdf, .png, .tif, etc., see the MATLAB [15] Documentation.

3. Visualization of concrete spalling after fire test

3.1. Experiment description

Here, we focus on a blast and fire experiment described in our previous work [16,17]. Within the experiment, six reinforced concrete floor slab panels of the dimensions of 3600 × 1000 × 150 mm were tested. They were made of normal concrete C30/37 (according to [18]) in three variants – without fibres (referred to as material 1), with polypropylene fibres (material 2), and with steel fibres (material 3). For each material, two panels were manufactured and one of them was subjected to blast loads before the fire test. Hereafter, the reference panels (without blast exposure) are denoted as “panels a”, and the panels subjected to blast loads before the fire test are denoted as “panels b”, see also [16,17].

All panels were placed in a fire furnace, loaded by constant mechanical loads, and exposed to the standard fire exposure (ISO 834 fire curve, see e.g. [19]) for 135 minutes. During the fire experiment, the temperature evolutions within the panels as well as their deflections were recorded.
After a cooling period of one day, the panels were removed from the furnace and prepared for further investigation, including the measurement of concrete spalling depths, see figure 1. A detailed description of the experiment can be found in [16,17].

![Figure 1](image1.png)

**Figure 1.** Reinforced concrete floor slab panels after the fire test. Concrete spalling on the heated (bottom) surfaces of the panels. Notation: 1 – concrete without fibres, 2 – concrete with polypropylene fibres, 3 – concrete with steel fibres; a – reference panels (without blast exposure), b – panels subjected to blast loads before the fire test. See also [16,17].

As can be seen in figure 1, no spalling occurred for panels 2a and 2b made of concrete with polypropylene fibres. Hence, the following analysis and visualization of concrete spalling is focused on the other panels - 1a, 1b, 3a, 3b.

### 3.2. Measurement of the spalling depths

The spalling depths were measured manually by a depth slide gauge in a regular grid of 100 mm × 100 mm, see figure 2. The obtained data (spalling depths, coordinates of the measurement point) were stored in a .xlsx file for a subsequent analysis.

![Figure 2](image2.png)

**Figure 2.** Measurement of spalling depths by a depth slide gauge in a regular grid of 100 mm × 100 mm, see also [16,17].
3.3. Data visualization and analysis
The data visualization is conducted as described in algorithm 1. The analysed area (heated surface of the panel) as well as the measurement points are displayed in figure 3a. In this case, the measurement points lie on the boundary of the analysed area, and hence, no extrapolation of the data is needed. The interpolation methods mentioned above (linear, nearest, and natural, see the MATLAB [15] Documentation) are illustrated in figures 3b–c, where the data are visualized by filled contour plots (so called “spalling maps”) using MATLAB [15] contourf function. Other types of graphs that can be used for the data visualization as well as their comparison with a photograph of the analysed panel are presented in figure 4.

![Figure 3](image)

**Figure 3.** (a) Geometry of an analysed panel. The analysed area (heated surface) is highlighted in gray color; the measurement points are plotted by plus marks. (b–d) Example of the spalling maps on the 3a panel obtained by different interpolation methods: linear (b), nearest (c), and natural (d), see the MATLAB [15] Documentation.

As mentioned above, a descriptive statistical approach can be employed in order to analyse the measured data. Here, we can illustrate this approach by determining the maximum and mean values of the spalling depths for the analysed panels, see table 1 (cf. e.g. [1–12]).

A more detailed study and discussion of the spalling behaviour of the analysed panels are out of the scope of this paper and will be done in our future work.
Figure 4. Spalling visualization on the 3a panel. (a) Spalling isoline map obtained by MATLAB \[15\] contour function. (b) Surface plot of a part of the panel obtained by MATLAB \[15\] surf function. (c) Photograph of the panel. See also \[16,17\].

| Spalling depth (mm) | Panel 1a | Panel 1b | Panel 3a | Panel 3b |
|---------------------|----------|----------|----------|----------|
| Maximum             | 26       | 27       | 32       | 34       |
| Mean                | 4.1      | 4.0      | 7.0      | 10.8     |
4. Visualization of UPV data of concrete bridge decks before and after blast exposure

4.1. Experiment description

The applicability of the presented data visualization tool can also be illustrated by analysing the UPV measurement results obtained during blast experiments described in [17, 20]. Within the scope of the experiments, six reinforced concrete bridge decks of the dimensions of 6000 × 1500 × 300 mm were tested. They were denoted #12–17 in [17, 20], which we adopt here. The specimens were made of high performance concrete (specimens #12–15) or ultra-high performance concrete (specimens #16 and #17) with high-strength steel fibres.

Each deck was exposed to 25 kg TNT blast loads with the charge placed in the specimen centre near the upper surface.

After the blast exposure, the specimen damage in the form of cracking, spalling, deflection, delamination, and puncture was measured and analysed. The measurement of the surface damage (spalling, puncture) was conducted manually using the procedure described in the previous example in section 3 (manual measurement of the damage depths in a regular grid). The analysis of the damage and its scale – spalling and puncture areas and volume, see [20, Tab. 2], was performed by a semi-manual procedure described in detail in [21, Section 2.3, Fig. 4]. The results presented in [20, Tab. 2] can easily be compared with the outputs obtained by the automatic procedure presented in this paper. However, such comparison is beyond the scope of this paper and will be done in our future work.

In order to determine the material degradation due to the blast exposure, UPV measurements were performed on all decks before and after the experiment, as described in the following sections.

A detailed description of the experiment can be found in [17, 20]. Some preliminary results of the visualization and analysis of UPV data using the presented procedure have already been published in [22].

4.2. UPV measurements

The UPV measurements were performed by an ultrasonic test device with two transducers placed on the opposite surfaces of the specimen – i.e. using the direct method, see e.g. [13, 14]. The device is shown in figure 5. The measurement points were defined by a regular grid of 200 mm × 200 mm (specimen #13) or 300 mm × 300 mm (the other specimens), see [20, Figs. 7–11]. The obtained data (transit time, pulse velocity) were stored in a .xls file for a subsequent analysis.

![Figure 5. Ultrasonic test device used for the UPV measurements, see also [16, 17].](image-url)
4.3. Data visualization and analysis
The data visualization is conducted as described in algorithm 1. In this example, we use the nearest interpolation method and the linear extrapolation method, see the MATLAB [15] Documentation. The UPV data measured on specimen #12 before the blast exposure are shown in figure 6.

Figure 6. The UPV data measured on specimen #12 before the blast exposure: (a) Geometry of the analysed specimen, positions of the measurement points, measured values of the pulse velocity \( V \) (m/s). (b) Isoareas obtained by MATLAB [15] \texttt{contourf} function. (c) Isolines obtained by MATLAB [15] \texttt{contour} function. (d) Line graphs for selected sections. See also [22].
The UPV data measured on specimen #12 after the blast exposure are shown in figure 7a. Due to the damage (puncture) of the central par of the specimen, the UPV data for the measurement points in this area could not be obtained, see figure 7a.

![Figure 7](image-url)

**Figure 7.** The UPV data measured on specimen #12 after the blast exposure: (a) Measured values of the pulse velocity $V$ (m/s); for the points with the X-values, the data were not obtained. (b) Isoareas obtained by MATLAB [15] `contourf` function; the X-values are replaced by pulse velocity $V = 343$ m/s. (c) Isolines obtained by MATLAB [15] `contour` function; the X-values are replaced by pulse velocity $V = 343$ m/s; a limit for the visualization is set to the lowest measured value, $V = 943$ m/s. (d) Relative values of the pulse velocity. See also [22].
The lack of data for the damaged part of the specimen has to be solved during the visualization process. During the development of the presented data visualization tool, the following approaches have been employed:

- define the boundary of the damaged area, set it as the boundary of the analysed geometry in step 2 of algorithm 1, and perform the interpolation/extrapolation process only for the undamaged parts of the specimen; the boundary of the damaged area can be obtained by manual measurements or by an image processing method;
- use MATLAB [15] NaN (not a number) values for the measurement points in the damaged area and conduct the interpolation/extrapolation process for the whole specimen face area;
- set the pulse velocity in the damaged area to a specific value, e.g. $V = 0 \text{ m/s}$, as used in [22], or $V = 343 \text{ m/s}$ (pulse velocity in normal air, see e.g. [23, Tab. 5.1]), and conduct the interpolation/extrapolation process for the whole specimen face area.

Here, we use the last-mentioned approach with $V = 343 \text{ m/s}$ for the measurement points in the damage area, see figure 7b.

For a better illustration of the damage (puncture), a limit can be set, e.g. to the lowest measured value. Below this limit, the values obtained by an interpolation/extrapolation process are excluded from the visualization, as shown in figure 7c.

The material degradation and damage of the specimen due to the blast exposure can be analysed by comparing the UPV data measured before and after the blast exposure. This can be expressed by the relative values of the pulse velocity defined as the pulse velocities measured after the blast exposure divided by the corresponding initial values (before the blast exposure), see figure 7d.

Comparison of the obtained isolines of the pulse velocity after the blast exposure with a photograph of the analysed specimen is presented in figure 8.

Figure 8. Comparison of the obtained isolines of the pulse velocity after the blast exposure with a photograph of the analysed specimen #12; author: J. Stöhr, see also [22].

Figure 9. Areas with specific ranges of the relative pulse velocity for specimen #12 obtained by an automatic procedure, see also [22].
A quantitative investigation of the specimen properties can be conducted by descriptive statistical analysis (mean values, standard deviation) of the measured UPV data. The material degradation and the damage of the specimen due to the blast exposure can also be quantified by determining surface areas with specific ranges of the relative pulse velocity, see figure 9. Some preliminary results of this analysis have been presented in [22]. A more detailed study and discussion of the blast resistance of the analysed specimens will be done in our future work.

5. SVDult software
The developed data visualization tool has been included in a freely available scientific software SVDult [24]. The software, including its graphical user interface, has been developed in MATLAB [15] environment. The software will be described in detail in our future work.

6. Conclusions
In the paper, a data visualization tool, based on an in-house MATLAB code, was described and its applicability and versatility were shown on illustrative examples. The examples were focused on visualization and analysis of the data obtained from fire and blast experiments. The developed data visualization tool has been included in a freely available scientific computer program with a graphical user interface.

Acknowledgments
This work has been supported by the Czech Science Foundation, project No. GA17-23067S, which is gratefully acknowledged.

References
[1] Mindegia J C, Pimienta P, Carré H and La Borderie C 2009 1st International Workshop on Concrete Spalling due to Fire Exposure pp 150–167
[2] Mindegia J C, Pimienta P, Carré H and La Borderie C 2013 European Journal of Environmental and Civil Engineering 17 453–466
[3] Guerrieri M and Fragonemi S 2013 MATEC Web of Conferences 6 01002
[4] Guerrieri M and Fragonemi S 2016 Journal of Materials in Civil Engineering 28 04016164
[5] Mohd Ali A Z, Sanjayan J and Guerrieri M 2017 Journal of Materials in Civil Engineering 29 04017237
[6] Mohaghegh A M, Silfwerbrand J, Arskog V and Jansson McNamee R 2017 Nordic Concrete Res. 57 89–102
[7] Hager I, Mröz K and Tracz T 2018 MATEC Web of Conferences 163 02004
[8] Krzemien K and Hager I 2015 Procedia Engineering 108 285–292
[9] Yan Z G, Shen Y, Zhu H H, Li X J and Lu Y 2015 Fire Safety Journal 71 86–99
[10] Ozawa M, Uchida S, Kamada T and Morimoto H 2012 Construction and Building Materials 37 621–628
[11] Chlepková M 2011 INGEO 2011 – 5th International Conference on Engineering Surveying pp 295–300
[12] Yi N H, Choi S J, Lee S W and Kim J H J 2015 Fire Safety Journal 71 123–133
[13] Bungey J H, Millard S G and Grantham M G 2006 Testing of Concrete in Structures (Taylor & Francis)
[14] Ravich Kumar N S M, Barkavi T and Natarajan C 2018 Journal of Building Pathology and Rehabilitation 3 6
[15] MATLAB 2015 Version 8.6.0 (R2015b) The MathWorks, Inc., Natick, Massachusetts, United States
[16] Stefan R, Foglar M and Fládr J 2016 Beton TKS 16 42–48 [in Czech]
[17] Foglar M, Hájek R, Štefánik J and Stöhr J 2016 Performance Investigation of Cementitious Composites Subjected to Extreme Loading. Experiments, Modelling. Technology (CTU in Prague) [in Czech]
[18] EN 206+A1 2016 Concrete – Part 1: Specification, performance, production and conformity (CEN)
[19] EN 1991-1-2 2002 Eurocode 1: Actions on structures – Part 1-2: General actions – Actions on structures exposed to fire (CEN)
[20] Foglar M, Hajek R, Fládr J, Pachman J and Stoller J 2017 Construction and Building Materials 145 588–601
[21] Foglar M, Hajek R, Kovar M and Stoller J 2015 Construction and Building Materials 94 536–546
[22] Stöhr J 2016 Non-destructive assessment of damage caused by blast overpressure to reinforced concrete panels PhD Workshop 2016 (Dept. of Concrete and Masonry Structures, FCE CTU in Prague) [in Czech]
[23] Sinclair I R 2001 Sensors and Transducers 3rd ed (Newnes)
[24] Stefan R and Foglar M 2015–2019 SVDult – Software for visualization of data obtained by ultrasonic analysis of concrete specimens CTU in Prague. http://people.fsv.cvut.cz/www/stefarad/software.html