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Non-destructive testing of the construction material of fire-damaged building structures with a vibration measuring device

Abstract

During fire incidents, the strength properties of the construction materials of various building structures may change as a result of the fire. After a fire, it is very important to determine the degree of damage to the building, primarily from the point of view of life protection, and in order to explore later restoration options. The so-called Impact-Echo (IE) measuring method, which can be applied on site and enables non-destructive testing, can help in this. During on-site measurements, zones with changed material properties can be detected and spatially delimited by mechanical vibrations. In this study, we examine which vibration meter is most suitable for on-site, non-destructive testing of the materials of fire-damaged building structures.

Keywords: construction materials of building structures, fire incidents, Impact-Echo (IE) measurement method, vibration meter

Tűzkárosodott épületszerkezetek építési anyagának roncsolásmentes vizsgálata rezgésmérő eszközzel

Kivonat

A tűzesetek során a különböző épületszerkezetek építési anyagainak szilárdsági tulajdonságai megváltozhatnak a tűz hatására. A tűzesetet követően nagyon fontos az épületkárosodás mértékének meghatározása elsődlegesen életvédelmi szempontból, illetve a későbbi helyreállítási lehetőségek feltárása érdekében. Ebben jelenthet segítséget a helyszínen alkalmazható, roncsolásmentes vizsgálatot lehetővé tevő ún. impulzus kalapács (IE) mérési módszer. A helyszíni mérések során mechanikai rezgésekkel kimutathatók és térben lehatárolhatók a megváltozott anyagtulajdonságú zónák. Jelen tanulmányban vizsgáljuk, hogy mely rezgésmérő alkalmas leginkább tűzkárosodott épületszerkezetek anyagainak helyszíni, roncsolásmentesen vizsgálatára.

Kulcsszavak: épületszerkezetek építési anyagai, tűzeset, impulzus kalapács mérési módszer, rezgésmérő

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Introduction

During fire incidents, the strength properties of the construction materials of various building structures may change as a result of the fire. After a fire, it is very important to determine the degree of damage to the building, primarily from the point of view of life protection, and in order to explore later restoration options [1]. After a fire, non-destructive testing methods of the construction materials of building structures are increasingly used to supplement the information obtained by destructive methods. During on-site measurements, zones with changed material properties can be detected and spatially delimited by mechanical vibrations [2]. One of the most commonly used non-destructive testing methods is the so-called IE measurement method [3], [4], [5]. The IE method is primarily used to detect concrete defects [6], [7] and determine the concrete thickness [8]. Studies conducted in recent years have confirmed that the so-called IE measurement method can also be effectively used to assess the condition of the construction materials of fire-damaged building structures [9], [10].

The theoretical basis of the method is mechanical wave propagation in solid bodies

In general, materials behave as elastic media against small deformations. Elastic waves can be raised in them, and an ideal elastic deformation takes place in them. In the case of the IE method a small deformation is created on the surface of the medium (e.g., with a hammer, rubber hammer, piezo or magnetostriction vibration transmitter) [11]. As a result of the mechanical impulse, a field wave is raised in the medium [12]. Depending on the geometry (size, shape) of the medium, different types of mechanical waves are generated in the body.

The generated mechanical waves can be classified into the following groups based on the way the energy propagates:

a) longitudinal, transverse, surface waves (Rayleigh waves),
b) expansion or tube waves and
c) plate or Lamb waves.

Description of mechanical waves by wave equation

The equation of a one-dimensional harmonic wave can be given in the form below.

$$u(x,t) = A * \cos[\omega * t - k * x + \varphi 0]$$

where

A – is excitation amplitude,

ω – circular frequency,

t – time,

k – wave number,

x – location,

$\varphi 0$ – initial phase or phase shift.

In real space and material, the propagation function is modified by the material's internal properties and its spatial distribution [13], which is why the response function is a transient wave that fades away during impulse-type excitation (we measure this in practice). We use an impulse-type source because it is difficult to fasten continuous emitters (e.g., loudspeakers) into the building structure to be tested.

Characteristics of the mechanical wave

The constants included in the mathematical solution of the wave equation must be given material properties for their everyday use, i.e., in material structure tests with mechanical vibrations.

In real bodies, mechanical waves propagate in a complicated way: they interfere, undergo diffraction, bend, attenuate, their frequency content changes due to the filtering effect of the medium, and the useful signal is loaded with external noise (e.g., electrical and mechanical noise).

Knowledge of the propagation conditions of mechanical waves is necessary to recognize individual wave types. Different types of mechanical waves propagate at different velocities in the examined material and structure. We can reveal inhomogeneities with the propagating mechanical vibration only if the size of the examined space is comparable to the magnitude of the wavelength and can also be characterized by a change in acoustic impedance.

Theory of acoustic integrity testing

The test is based on the physical phenomenon according to which a mechanical impulse (such as a hammer blow) transferred to a concrete or other solid material (stone, brick, etc.) structure creates a wave in the structure. The wave, distorted, runs through the material and describes the temporal location of the changes (distortions), which can be evaluated with mathematical post-processing. In this way, the physical characteristics and fault locations of the structure can be determined.

The course of the measurement signal in the construction material of the examined fire-damaged building structure

The wave carrying the measurement signal (its frequency is in the range of audible sound approx. 800 – 1000 Hz, not ultrasound) is created by hitting a hammer. The hammer can be steel, rubber of different hardness or plastic. A sound wave is generated by the impact measured on the object being tested [14], which runs through the object axially (along the longitudinal axis) and is reflected from the interface, from the lower end of the object, and from the disturbance points. Disturbances (reflections) are determined by changes in the shape (diameter, thickness, etc.) and material (density, elasticity) characteristics of the object, as well as attenuation due to the stratification (material characteristics) of the medium around the object.

Measuring and recording the signal

Regardless of the evaluation method, acoustic signals are electrically measured and stored using similar procedures. The mechanical (acoustic) wave created by the hammer is measured with a signal transducer (measuring head) made of piezo-ceramics. The acceleration of the mechanical wave, the amplitude of the reflection, and the propagation time (time function) are measured on the surface of the object. Based on the measurement arrangement, the signal package contains the information on the subject mentioned above. In the measuring head, the mechanical vibrations are transformed into electrical voltage, which is measured, qualified and stored by a digital storage oscilloscope controlled by a computer converted to measurements.

Evaluation of measurement results

During the evaluation of the results of the integrity test, the digitally recorded signal, which due to the nature of the sensor describes the change in acceleration over time, is subjected to additional signal processing mathematical operations. Evaluation can be done using two methods. Using the Impact-Echo method or the sound reflection method.

Types of vibration meters that can be used during measurement

Capacitive acceleration sensors

Here, the seismic mass acts on a capacitor serving as a spring, the capacity of which changes with the effect of the force. The capacitance measuring bridge built into the sensor provides the output voltage signal proportional to the acceleration. Sensors built on this principle are excellent for measuring linear accelerations and relatively slow (low-frequency) vibrations.

Piezoresistive sensors with a strain gauge-based sensor element

In this type, the sensor element is fixed parallel to a spring system in the sensor. In case of mechanical load, its resistance changes. With proper power supply, the output signal is voltage. Piezoresistive sensors (Photo 1.) can be used to measure linear acceleration, vibration and shock.

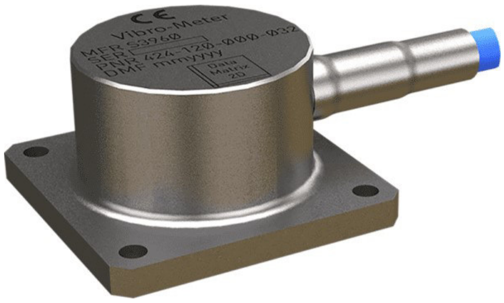

Photo 1.: Piezoresistive sensor [15]

Piezoelectric sensors with a quartz or a ceramic-based sensor element

The sensors (Photo 2.) use the charge-generating property of a quartz or a ceramic-based sensor element. Due to the finite resistance of the sensor element, these sensors can only be used to measure dynamic accelerations (vibrations) and shock. The output signal is electric charge or voltage (which in some models has a built-in charge amplifier). Both types of designs have special – partially overlapping – areas of application.

Photo 2.: Piezoelectric sensor [16]

Inductive acceleration sensors

The sensors are based on a differential transformer, the core of which acts as a seismic mass and changes the inductance due to acceleration. The sensors (Photo 3.) built like that can be used to measure linear accelerations and slow (low-frequency) vibrations.

Photo 3.: Inductive sensor [17]

Geophone

The geophone is shown in Photo 4. below. It generates a voltage induced by the displacement of an oscillating coil dampened by a spring in a constant magnetic field. The induced voltage is proportional to the velocity change. Its transfer function can be controlled by resistance (electrodynamic brake).

Photo 4.: Geophone [18]

MEMS sensor

MEMS is an acronym (Micro Electro Mechanical Systems, Micro electronic and mechanical systems), within which we only deal with the capacitive acceleration sensor.

The sensor (Photo 5.) measures the acceleration of a mass suspended on polysilicon springs using the capacitive principle. The deflection and displacement of the polysilicon structure, which is proportional to the acceleration, is measured by a capacitor with a differential connection. Compared to conventional sensors, the size of MEMS is the smallest (5 × 5 × 2 mm + the size of the auxiliary electronics).

Photo 5.: MEMS sensor [19]

A comparison of the different types of vibration sensors is shown in Table 1.

Table 1.: Comparing different types of vibration sensors [own table]

	Capacitive	Piezo-resistance	Piezoelectric	Geophone	MEMS
Measured property	Acceleration	Acceleration	Acceleration	Velocity	Acceleration
Frequency range [Hz]	0–1.000	0–150.000	0.2– 900.000	0.1–40	10–1.000
Impedance	Large	Small	Large	Medium	Small
Size	Medium	Medium	Small	Large	Small
Temperature range	-55… + 120	-25… + 95	–270…+650	–40…+100	-40...+125
Attenuation	Yes	Yes	No	Yes	No
Power supply	Unregulated voltage	Voltage regulator	No	No	Yes
Evaluation	Voltage meter	Bridge amplifier	Charging amplifier	Bridge amplifier	Voltage meter
Costs	Medium	Small	High	High	Small
Can be overloaded	No	No	Yes	Attenuation dependent	Yes

Instruments used for measurement

We used the following instruments for our measurements:

- Digital storage oscilloscope manufactured by Iwatsu DS-8601
- Impulse hammer
- Special hammers

- 100 × 10 × 4.5 cm pine board (measuring device)
- Sensors: KD-2A type vibration sensor basic sensor, MEMS, ultrasound transmitter, piezo plate sensor

Measurement arrangement

With the two types of measurement arrangements used during our measurements, our goal was to determine the "real" velocity of the measuring device and to compare the tested sensors under the same conditions.

Transient wave type velocity measurement

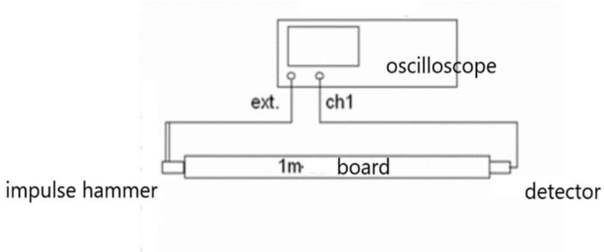

Figure 1.: Transient wave type velocity determination edited by the author

$$c_{wood} = L/t$$

where

L – the length of the board,

t – the running time of the wave.

With the above measurement arrangement, c_{wood} = 1/0.29875 = 3.347 m/ms = 3.347 m/s velocity was obtained.

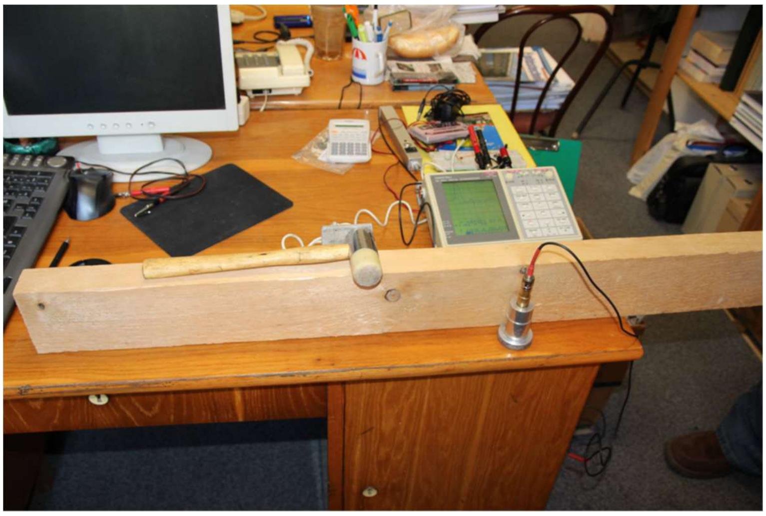

Photo 6.: Devices used for velocity measurement [own photo]

The measurement set-up (Figure 1. and Photo 6.) is used to determine the "real" velocity of a test body of known length. We start the measuring wave with the impulse hammer, and when struck, this provides the zero time instant of the time difference. The transit time is given by the time of the maximum signal formed on the sensor. This can be seen in the following Photo 7.

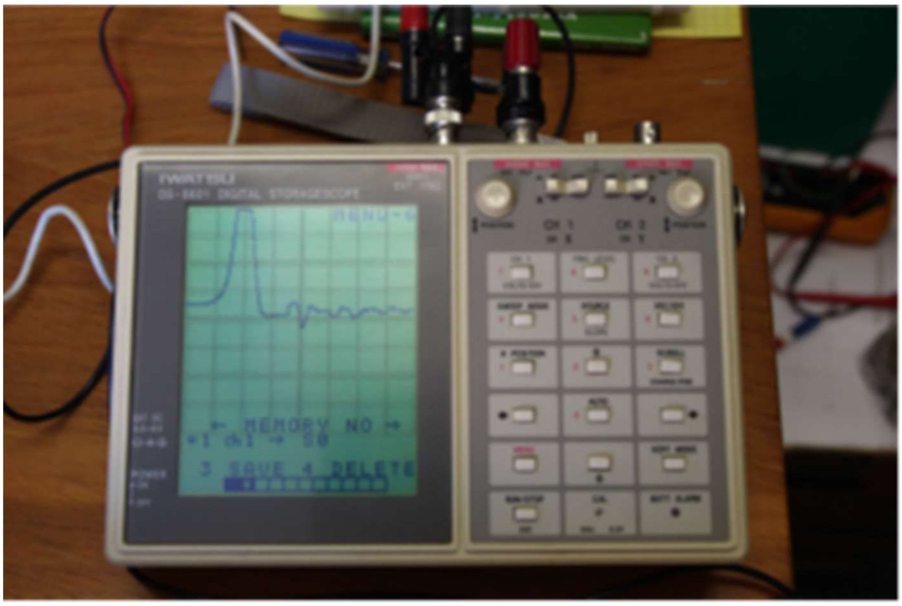

Photo 7.: Velocity measurement on an oscilloscope [own photo]

In the figure (Figure 2.) below, we show the following, which were created using the DADISP processing program:

W1 is the "raw" signal,

W2 is the normal signal (amplitudes are set between -1 and +1 for comparability),

W3 is the energy function (signal amplitude squared),

Generation of W4 velocity function by integration from the acceleration function,

W5 autocorrelation function with positive peak selection,

W6 power spectrum with positive peak selection.

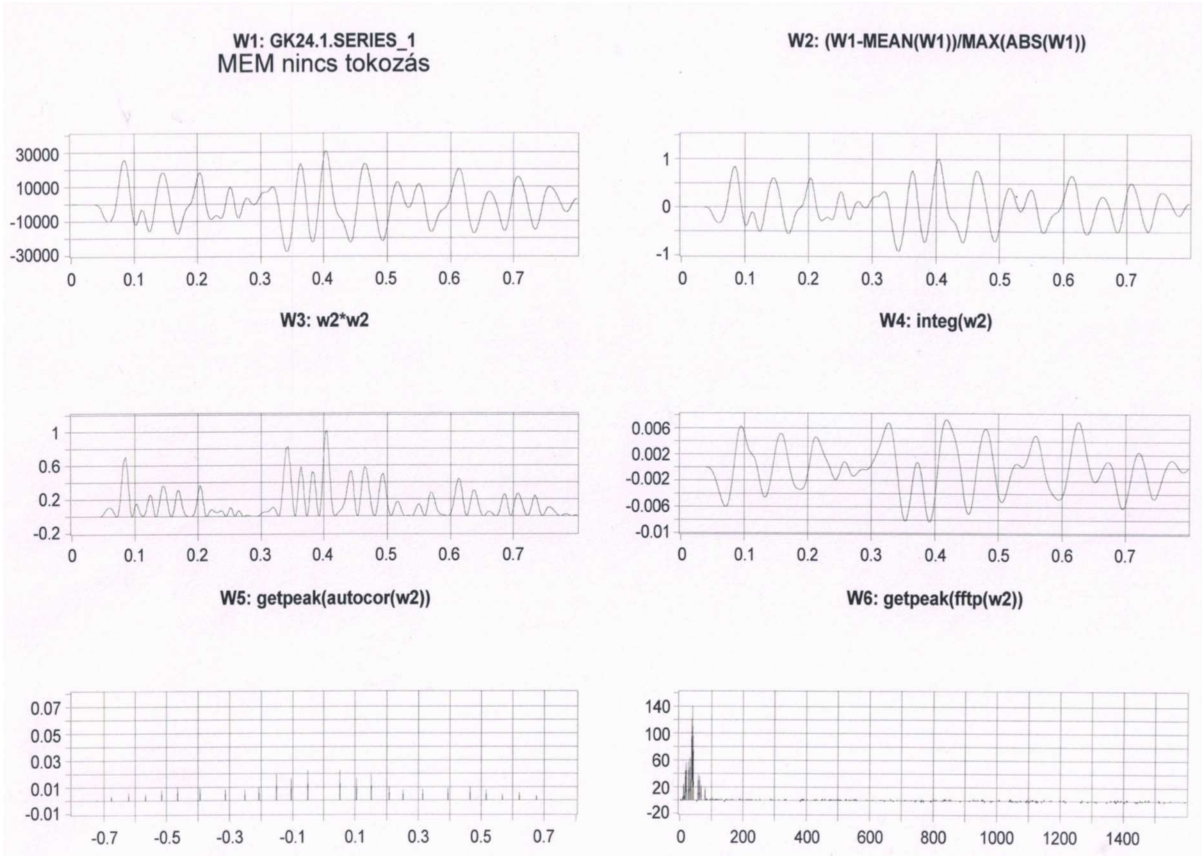

Figure 2.: Velocity measurement result edited by the author

Reflection length measurement

When comparing the tested sensor types, we used reflection length measurement (Figure 3.), where the test signal travels twice through the test tube. The evaluation was carried out using the sound reflection method.

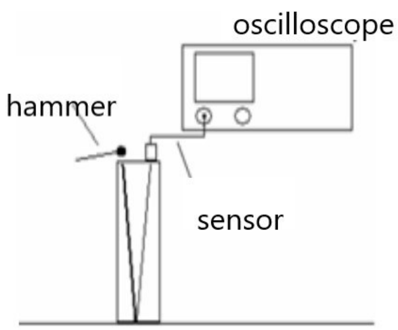

Figure 3.: Reflection length measurement instruments edited by the author

Results of measurements with different types of sensors

The purpose of the comparative measurements with different types of sensors is to simulate the conditions of measurement on a concrete test piece on a special measuring device, and to compare the measurement results. The special measuring device is a wooden body, the acoustic properties of which are almost identical to those of concrete, and its geometric size is already sufficient for evaluable propagation velocity and reflection length measurements. It is good to use the wooden measuring body because its wave velocity is almost the same as that of the medium-quality concrete:

$$Cwood = \sqrt{\left(\frac{Ewood}{\rho wood}\right)} \approx \mathrm{Cconcrete} = \sqrt{\left(\frac{\mathrm{Econcrete}}{\rho \mathrm{concrete}}\right)}$$

where:

Cwood: wave velocity in wood

Ewood: elasticity modulus of wood

ρwood: density of wood

Cconcrete: wave velocity in concrete

Econcrete: elasticity modulus of concrete

ρconcrete: density of concrete

The reason for this is that the ratio of the elastic modulus and density of wood is almost the same as that of the concrete [20].

Among the comparison aspects of the sensors, the highest transmitted frequency component of the frequency spectrum of the sensors was the most important. This is important because it is a determining element in processing (determination of the length), as it determines the accuracy of the measured distance based on the formula $\lambda = c/f$. Another selection consideration is the signal level (output voltage) of the sensor, which we did not examine at this time because most sensors were not encapsulated and encapsulation changes the output signal level.

The frequency was highest for the MEMS without encapsulation and the UH head, then the encapsulated MEMS, and finally the KD-2A sensor (Table 2.). In addition to the mechanical design of the piezo chip, it did not give an appreciable result.

Table 2.: Result of measurements edited by the author

	KD2A reflection	UH transceiver	Piezo chip	MEMS without encapsulation	MEMS with encapsulation
ΔT[ms]	0.643	0.659	-	0.604	0.603
c[m/ms]	3.110	3.035	-	3.311	3.317
fmax [kHz]	5.0	5.0; 17.0	-	40	11.25

Conclusion

Based on the above tests, it can be concluded that a vibration meter with a MEMS acceleration sensor is the most suitable for the on-site non-destructive examination of the material of fire-damaged building structures.

Advantages and disadvantages of MEMS acceleration sensors:

- their size is small, they can be easily attached to the test surfaces, so they are easy to handle in terms of measurement technology,
- they are cheap,
- their measurement frequency limit is approx. 5000 Hz, the related detection limits are approx. 30 - 50 cm long,
- their disadvantage is that they require an energy source for their operation.

With the further development of the vibration meter built on the MEMS acceleration sensor, the following may be possible:

- the measurement frequencies can be further increased, thus the error locations can be more accurately delineated
- small loudspeakers can be used as a vibration source by solving the issue of energy coupling
- by using mixed-frequency vibration sources (a combination of low-frequency and high-frequency vibrations), measurements can be made simpler. Fault locations of different sizes can be determined simultaneously and the size resolution can be further increased.

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