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A methodology for laboratory testing of rockbolts used in underground mines under dynamic loading conditions

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Synopsis

Underground mining is subject to various natural hazards such as seismic events, rockbursts, fire, and gas (methane). In general, an increase in the extraction depth causes an increase in the likelihood of these hazards, especially seismic activity and rockbursts. Dynamic phenomena such as rockbursts and tremors have been recorded on six continents: Europe (Poland, Russia, Czech Republic, Germany, and Slovenia), Asia (India, and China), North and South America (USA, Canada, and Chile), Africa (South Africa), and Australia. To select appropriate mine working supports for such dynamic phenomena, the performance characteristics of such support types must be determined under both static and dynamic load conditions.

This article presents information regarding the application of rockbolts in Polish underground hard-coal mines. Dynamic phenomena occurring in the mines from 2004–2013 are also characterized. A methodology developed at the Central Mining Institute (GIG) for the laboratory testing of rockbolts is presented. In this methodology, the bolts are loaded by the direct impact of a free-moving mass (up to 20 000 kg) at speeds of up to 1.2 m/s. The facilities at GIG used to test the support under static and dynamic load conditions are characterized, and the results of laboratory tests on yielding bolts with a nominal capacity of 420 kN are presented. These types of bolts are commonly used for reinforcing steel arches and the surrounding rock mass in Polish coal mines. The results of the laboratory testing of yielding bolts are discussed..

Keywords
underground hard-coal mining, rockbolts, dynamic load, laboratory testing methodology, yielding bolts.

Introduction

Seismic events such as rock bumps and tremors occur with great frequency during underground mining. These phenomena have been reported in such countries as Poland, Czech Republic, Germany, France, Slovenia, Russia, India, China, the USA, Canada, Chile, South Africa, and Australia (Bräuner, 1991; Potvin, Hudyma, and Jewell, 2000; Kidybiński, 2003; Driad-Lebeau *et al.*, 2005; Li, Cai, and Cai, 2007; Whyatt and Loken, 2009; Durrheim and Riemer, 2012; Holub, Rušajová, and Holečko, 2011). Descriptions of the dynamic events and their effects in the form of damage to or destruction of supports have been presented in many publications, both for hard-rock mines as well as for coal mines (Brauner, 1991; Dubiński and Konopko, 2000; Heal, 2010; Heal and Potvin, 2007; Simser, Joughin, and Ortlepp, 2002; Kaiser and Cai, 2012; Cai, 2013; Nierobisz, 2013; Mark, 2014; Masny and Prusek, 2015). One of the main goals of the research has been to develop methods, criteria, and guidelines for the selection of an optimal and safe support for mine workings located in areas of rock bumps or tremors. Example of such studies include the Canadian Rockburst Support Handbook (Kaiser, McCreath, and Tannant, 1996), or the principles presented in the literature (Li, 2010; Cai, 2013). The general principle in mine workings subjected to the risk of a dynamic load is to utilize a yielding support (yielding bolts) or rebar bolts of various lengths. This support can be connected to other types of support such as mesh or shotcrete. All parts of a support system must absorb the dynamic energy released during the tremor or rockburst as well as minimize the deformation (convergence) of the working. A number of construction solutions have been applied to meet the principles of a yielding support in regions of burst-prone ground. There are numerous examples of bolts capable of transferring dynamic loads, including Cone Bolts, Durabar, D-Bolts, Roofex, Garford, Yield-Lok, and CRLD (constant resistance-large deformation bolts) (Ortlepp, Bornman, and Erasmus, 2001; Neugebauer, 2008; Li, 2010, Campoli, Oldsen, and Wu, 2012; He and Sousa, 2014). However, according to Kaiser *et al.* (1996), due to practical and economic limitations it is not practical to provide an energy capacity greater than 50 kJ/m^2 for ground support. This level was termed the 'maximum practical support limit' (MPSL), and once reached, it is considered impractical to prevent damage to mine openings by increasing the amount or changing the type of ground support. Other strategic measures must then be taken to reduce the rockburst damage potential and workers' exposure to hazards (Heal, 2010).

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To optimize the support selection for mine workings subject to dynamic loads, laboratory and site tests were conducted. Laboratory studies on the impact of dynamic events on a support or their individual components have been performed at many test facilities. These facilities are located, for example, in Dortmund (Germany), Opava (Czech Republic), Carletonville (Savuka mine, Republic of South Africa), Greater Sudbury (Creighton mine, Canada), Noranda Inc. Technology Center (Canada), Walenstadt (Switzerland), and Kalgoorlie (Western Australia School of Mines, Australia) (Gaudreau, Aubertin, and Simon, 2004; Human and Ortlepp, 2004; Sosnica, 2008; Player, Villaescusa, and Thompson, 2008; Roth *et al.*, 2014). A comprehensive review of test rigs was provided by Hadjigeorgiou and Potvin (2008). Laboratory methods for testing dynamically loaded supports are described by Player, Villaescusa, and Thompson (2008). The authors have identified the following laboratory test methods for simulating dynamic loads:

- Direct impact of mass on an element
- Impact of the structure/element on a fixed element
- Impact of the structure/element on a moveable element, *e.g.* military collision testing of loaded railway wagons
- Impact of a mass on a load transfer mechanism or energy dissipation element.

A number of underground tests of supports subject to dynamic loads have been conducted in various mines, including coal, copper, zinc, and iron ore mines. From the perspective of test methodology, these tests can be divided into two main groups. In the first group, the measurements were performed during naturally occurring dynamic phenomena. In the second group, the measurements of dynamic events were conducted using explosives to simulate dynamic phenomena (Kidybiński, 1986; Stjern and Myrvang, 1998; Hagan *et al.*, 2001; Tannant, Kaiser, and McDowell, 1992; Masny, 2006; Heal and Potvin, 2007; Hadjigeorgiou and Potvin, 2008; Nierobisz, 2012).

Seismic activity experienced by Polish underground hard-coal mines from 2004–2013 is characterized in this article. The current status regarding the scope of the application of rockbolting in Polish coal mines is also described, along with the methodology of laboratory dynamic tests of the bolts developed at the Central Mining Institute, Katowice, Poland. The results of selected tests of the yielding bolts are presented.

General characteristics of hard coal mining industry in Poland

In 2013 there were 30 underground coal mines, producing 76.5 million tons of hard coal, in operation in Poland. The longwall method is used for the extraction of multiple seams. In 2013, 107 longwall panels were retreated with single entries (101 faces with natural roof caving into the gob and six with hydraulic backfilling). The average depth of the cover was 713 m; however, increasingly more collieries are exploiting coal deposits located at depths of approximately 1000 m. The significant extraction depth and the stress concentration caused by the interaction of edges or remnant pillars in the mined-out seams induces seismic activity and rockburst hazards in the mines (Stec, 2014). Information regarding seismic activity, rockbursts, numbers of accidents, and the lengths of damaged workings is shown in Figure 1 and Table I (Patyńska, 2014).

Table I shows the production of coal in Poland from 2003–2013, including the seams mined in areas subject to rockburst hazards, the number of rockbursts, the number of accidents, and the length of damaged workings (Patyńska, 2014).

The data presented in Figure 1 and Table I shows that hard coal production decreased from 102.5 Mt to 76.5 Mt from 2003 to 2013. During this period, 39% to 50% of coal production originated from seams located in rockburst areas. The number of rockbursts per year ranged from 1 to 5, resulting in 125 minor to severe accidents and 11 fatalities. Between 360 m and 3200 m of mine workings were destroyed or damaged as a result of rockbursts. Examples of damaged workings after rockbursts are shown in Figure 2.

According to Polish mining law, yielding-type support is required in coal seams extracted in seismic areas subject to rockburst hazards. Therefore, in most cases, yielding steel arches support the workings. The arches are a primary support installed in the working face during the development by roadheaders. The distance between the arches ranges from 0.5 m to 1.0 m. The steel arches have a V-shaped cross-sectional profile and a mass of between 25 kg/m and 36 kg/m. Under demanding conditions, the steel arches are reinforced using various types of support, mostly steel horseheads, wooden and steel props, or cribs. In recent years, bolts have been installed as reinforcement for steel arches and the surrounding rock mass (Prusek and Masny, 2013; Prusek, Masny, and Turek, 2014). Figure 3 shows the length of the developed workings in 2012 and the proportions of different types of supports used. An example of combined support (steel arches, fully grouted rebars, and yielding bolts) is presented in Figure 4.

The basic characteristics of bolts employed in Polish hard coal mines are listed in Table II.

Test facilities at GIG and bolt testing methodology under dynamic load conditions

Research on different types of supports used in underground coal mines has been conducted at GIG for many years. The tests are usually conducted by exerting static or dynamic loads on the support. The technical specifications of the dynamic test facility enable the examination of components with dimensions of up to 5×2×6 m (height × width × length) through the direct impact of a 1000–20 000 kg freely moving mass. The maximum impact energy is 500 kJ, and the initial

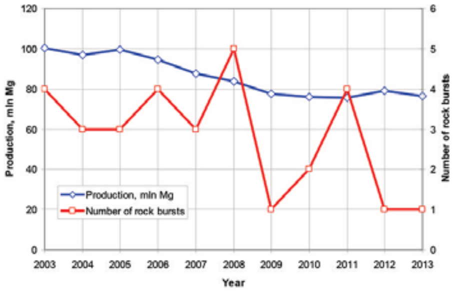


Figure 1—Hard coal production and the number of rockbursts in Polish coal mines from 2003–2013 (Patyńska, 2014)

Table I

Total hard coal production, production from seams located in rockburst areas, the accident rate, the number of rockbursts, the number of accidents, and the length of the mine workings damaged due to rockbursts from 2003–2013 (Patyńska, 2014)

Year	Total production	Extraction from seams located in rockburst areas		Accident ratio (accidents/ extraction)	No. of rockbursts	Rockburst accidents		Consequence in mine workings	
	Mt		% to general			Fatal	Other	Destroyed after rock fall (m)	Damaged, (m)
2003	100.40	41.8	40.9	0.18	4	2	16	110	145
2004	96.99	39.2	39.4	0.11	3	0	11	0	358
2005	99.50	41.0(1)	41.2(1)	0.13	3	1	12	0	270
2006	94.50	42.15	44.6	0.25	4	4	20	0	> 510
2007	87.40	44.6(1)	49.43(1)	0.11	3	0	10	0	530
2008	83.60	41.9(2)	50.12	0.31	5	0	26	0	710
2009	77.5	34.3(3)	43.8	0.06	1	0	5	0	101
2010	76.1	35.8(4)	47.04	0.18	2	2	12	30	87
2011	75.50	34.2(5)	45.36	0.08	4	1	6	0	168
2012	79.20	37.60	47.47	0.04	1	1	2	170(1)	210(1)
2013	76.47	36.90	48.25	0.07	1	0	5	50	113

(1)Approximate data

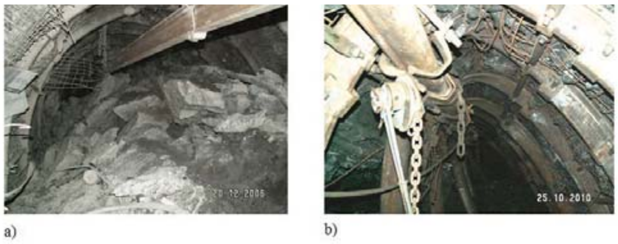

a)
b)

Figure 2—Damaged mine workings after rockburts. (a) Strong floor heave in the working, (b) deformation of steel arches

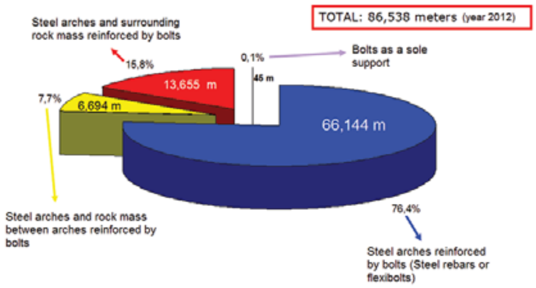
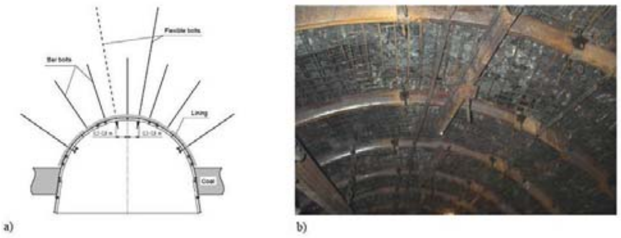


Figure 3—Length of developed mine workings in 2012 and the percentage use of different types of support (Turek, Prusek, and Masny, 2015)

load setting of the hydraulic cylinders can be up to 2 MN. Figure 5a shows the facility for the tests of yielding steel arches under static load conditions. The test facility for the lining support is shown in Figure 5b (Pytlik, 2013b, 2013c, 2014).

Bolt testing under dynamic load conditions

One issue that influenced research on methodologies for bolts subjected to dynamic loads was the lack of relevant Polish standards. Initially, this methodology (Pytlik, 2005) was designed to determine the dynamic resistance of yielding bolts under so-called 'explosive' rockburst conditions associated with the rapid disintegration of coal. This methodology assumed that a bolt should dissipate the impact energy without its elements being destroyed. The kinetic energy of the load is 25.0 kJ. A traverse with a mass of 2000 kg was used to exert the static load on a bolt prior to the dynamic impact. The test consisted of an impact by a 4000 kg free-falling mass. The parameters were selected in accordance



a)
b)

Figure 4—Examples of combined support of workings used in Polish hard-coal mines – steel arches and surrounding rock mass reinforced by fully grouted rebars and yielding bolts (Karlikowski and Kozek, 2013; Prusek, 2008)

Table II

Basic characteristics of the bolts used in Polish coal mines (Turek, Prusek, and Masny. 2015)

Bolt type	Diameter of bolt (mm)		Length of bolt (m)		Load-bearing capacity (kN)
	From	To	From	To	
Yielding bolts	20	30	3.0	12.0	280–430
Rebar bolts (rigid)	16	40	1.0	3.1	120–300
Injection bolts	20	43	1.3	11.0	50–430
Cuttable bolts	25	41	3.0	6.0	30–120
Expansion shell bolts	20	40	0.8	1.5	120
Cable bolts	18	18	6.0	6.0	300

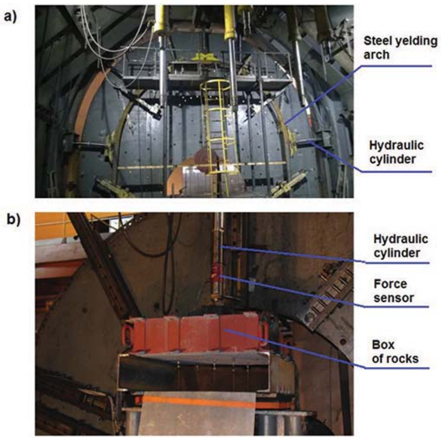


Figure 5—The test facilities at the Central Mining Institute (GIG). (a) Facility for testing steel arches at full scale, (b) facility for testing lining supports (*e.g.* shotcrete and TSL)

with the assumptions made for cases of 'explosive' rockbursts. This resulted in an impact speed of approximately 3 m/s (corresponding to the impact of the free-falling mass from a height of approximately 0.97 m). The high impact velocity used in the tests does not correspond to the rockburst model involving large masses of rock according to peak particle velocity (PPV) studies (Kidybiński, 1999).

The current research methodology (Pytlik, 2015) allows the dynamic load of a large mass (from 10 000 to 20 000 kg) to be applied to the bolt. The essence of the study consists of statically preloading a bolt by a traverse with a mass m_2. The main dynamic load is exerted by the impact of a free-falling mass m_1 from a height h. During the test, the loading speed v_u depends on the height h. The impact speed v_u is calculated under the assumption of a plastic collision of the masses m_1 and m_2. The speed v_o of the free-falling mass from the height h at the traverse at the moment of impact is calculated from

$$v_o = \sqrt{2gh} \tag{1}$$

where
h – height, m
g – acceleration due to gravity, m/s^2.

The speed v_o is not the speed of the dynamic load in the test of the support component. After the plastic collision, the system consists of combined masses m_1 and m_2. To calculate the speed v_u of the joined masses m_1 and m_2, the principle of conservation of momentum is used:

$$m_1 \cdot v_o = (m_1 + m_2)v_u \tag{2}$$

from which we obtain

$$v_u = v_o \frac{m_1}{m_1 + m_2} \tag{3}$$

According to Equation [3], a portion of the kinetic energy of the free-falling mass m_1 is lost to set the traverse (with mass m_2) in motion. The combined system of masses m_1 and m_2 has a lower velocity. The speed v_u is taken as the initial speed of the load. This value is substituted into the kinetic energy calculation formula of the combined masses m_1 and m_2:

$$E_k = \frac{1}{2}(m_1 + m_2)v^2{}_u \tag{4}$$

After substituting Equations [1] and [3] into Equation [4], we obtain

$$E_k = \frac{m_1^2}{(m_1 + m_2)} g \cdot h \tag{5}$$

where
m_1 – mass of free-falling mass, kg
m_2 – mass of traverse, kg
h – fall height of free-falling mass, m
g – acceleration due to gravity, m/s^2.

The average friction force F_t from the start of the bolt protrusion from the cylinder until the end of the feed of the bolt is calculated as follows:

$$F_t = \frac{\int_{t1}^{t2} F_d dt}{\Delta t} \tag{6}$$

where
t_1 – feed start time of the bolt from the cylinder, s
t_2 – feed end time of the bolt from the cylinder, s

Using the test facility, it is possible to examine both the mechanical components of the bolt (Figure 6a) as well as the bonded bolt in the steel cylinder (Figure 6b). The bolt is placed in a cylinder filled with concrete with a specified compressive strength.

During the test, the dynamic values of the breaking force and deformation of the bolts are measured. These parameters determine the stability of the support and are essential to the development of support projects for mine workings.

The development of the test methodology was guided by the analysis of seismic observations in Polish hard-coal mines (Dubiński and Mutke, 1996; Mutke, 2007) conducted in the region of the so-called near-field wave. This research showed that 90% of rock bumps occurred in the area where the PPV reached 0.05 to 1.0 m/s. Other data from the literature (Kidybiński, 2009) revealed that for PPV ≥ 0.4 m/s, there is a high risk of loss of stability of the mine workings. This implies the possibility of support destruction. This PPV value was also confirmed by Mutke (2012). In general, the PPV value is considered as a measure of the dynamic effect of the rockburst on the support (Potvin, Wesseloo, and Heal, 2010).

The speed of the free-falling mass in the GIG test facility, v_u, is not the same as the PPV on the surface of the mine workings. The methodology assumes that such correlation exists and applies only to the first impulse of the load and not to the wave motion. This is because in addition to the wave motion, there is another rock mass movement, which is a

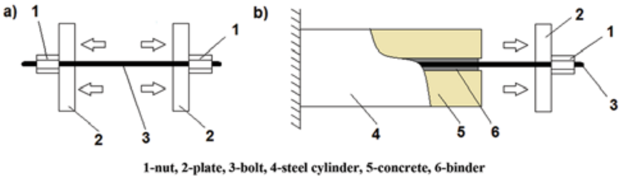


Figure 6—Schematic of the test method for bolts: (a) testing mechanical components, (b) pull-out test. 1-nut, 2-plate, 3-bolt, 4-steel cylinder, 5-concrete, 6-binder

common cause of the destruction of mine workings (Drzewiecki, 2002). This movement is associated with the motion of large volumes of rock mass initiated by the creation or propagation of discontinuities. The direction of this movement is consistent with the area with the most degrees of freedom.

The new methodology identifies five categories of bolts based on dynamic resistance. The classification is based on the initial velocity, v_u, of rock masses moving into the mine workings, as shown in Table III, where h is the fall height of the free-falling mass:

Using the developed methodology, the performance characteristics of bolts are determined under a dynamic impulse load. During the tests, the bearing capacity and yielding of the bolts are determined. These parameters are important for the design of rockbolts intended for use in areas subject to rockburst hazards.

Both the mechanical components of bolts (Pytlik, 2005, 2013a, 2015) – *i.e.*, the wires, washers, and nuts – as well as bolts bonded in a steel cylinder (Pytlik, 2015) can be tested in the facility. The cylinders are filled with concrete or a cement-mineral binder with a predetermined ultimate compressive strength. Based on Polish standards (PN-G-15092: 1999), the uniaxial compressive strength (UCS) should be greater than 50 MPa. The test facility also allows the adhesiveness of the resin or cement binder to the bolt wires to be checked. When testing bolts bonded to a steel cylinder, the length and dimensions can be adapted to the requirements of Polish standards (PN-G-15092: 1999). For bolts mounted sectionally in a cylinder, the standards require the test length to be at least 210 mm. For bolts secured along the entire length of the cylinder, a length of 1000 mm is assumed. In practice, it is often assumed that the bonding length of the bolts should not be less than 0.6 m. The initial tension of the bolts should not be less than 30.0 kN.

The relationship of the bolt dynamic resistance F_d as a function of load time t (at the desired impact speed v_u) characterizes the performance characteristics of a dynamically loaded bolt. The maximum force of dynamic resistance F_{dmax} is determined during the test. This value depends on the kinetic energy of the free-falling mass. The maximum impact speed v_u at which any element of the bolt is not damaged (the continuity of the material is not interrupted, and the bolt retains its functionality) is the basis for classifying these bolts into one of five categories of bolt impact resistance: W1–W5.

The mass of the free-falling mass in the test facility is taken as 24 000 kg, assuming that the average bulk density of rocks moving into the mine workings is 2400 kg/m³, and the volume is 10 m³.

Table III

Impact resistance categories for rockbolts (Pytlik, 2015)

Category	v_u (m/s)	h (cm)
W1	0.4	1.3
W2	0.6	3.0
W3	0.8	5.0
W4	1.0	8.0
W5	1.2	12.0

A full tension test of a bolt using this methodology is performed in two stages (Pytlik, 2015). In the first stage, the bolt's mechanical components are examined according to the scheme shown in Figure 7.

The examination of the bolt consists of the following:

(a) Preparing the bolt to be tested by securing it on both sides with nuts and washers
(b) Exerting a static load on the bolt (which simulates pre-tension of the bolt) by a traverse with instrumentation with a total mass m_2 = 4000 kg (traverse mass m_t = 3300 kg, instrumentation weight m_o = 700 kg). In the next step, the load is increased by an additional mass m_1 = 20 000 kg over 5 seconds. A positive test result is obtained if the bolts transfer the given load without damage (the continuity of the material is not interrupted)
(c) Unloading the bolt by raising the free-falling mass (m_1) to a predetermined height h (in the range from approximately 1 to 12 cm) corresponding to the given load speed v_u of 0.4 to 1.2 m/s
(d) Releasing the free-falling mass (with m_1 = 20 000 kg) into free fall from a height h above the traverse (m_2 = 4000 kg).

The test result in the first step is considered to be positive if any element of the bolt is not damaged (the continuity of the material is not interrupted, and the bolt retains it functionality).

During the bolt test, the instantaneous value of the dynamic resistance force F_d is recorded. From the obtained data, a maximum value F_{dmax} is determined. Before and after the test, the length of the bolt L is measured. This enables the elongation ΔL of a tested bolt to be determined.

Bolts that pass the first stage of research are tested in step 2. In this stage, a bolt is bonded to the steel cylinder. The scheme of the test for this step is shown in Figure 8.

The examination of the bolt in the second stage consists of the following:

(a) Installation of the bolt (Figure 8) into the steel cylinder at approximately 400 mm. TSM 70 adhesive with a nominal UCS of 70 MPa is used as the binder. After the installation, the bolt is left for 14 days. The binder achieves the required strength of UCS = 50 MPa over this time

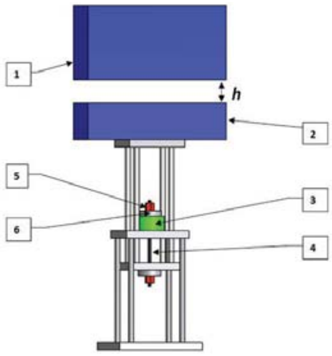


Figure 7—The test facility prepared for the examination of mechanical components under dynamic load with a free-falling mass: (1) free-falling mass (m_1), (2) traverse (with mass m_2), (3) force sensor, (4) bolt rod, (5) bolt nut, (6) bolt washers

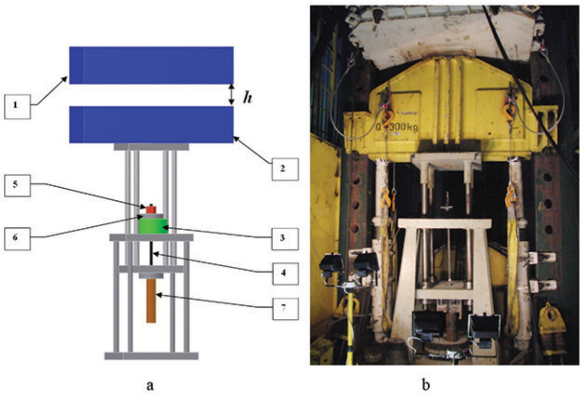


Figure 8—The test facility prepared for phase 2 testing applying a dynamic load to the bolt in a steel cylinder: (a) - scheme; (b) - photograph showing (1) the free-falling mass (m_1), (2) traverse (with mass m_2), (3) force sensor, (4) bolt rod, (5) bolt nut, (6) bolt washer, (7) steel cylinder

(b) A static load is exerted on the bolt (which simulates pre-tensioning of the bolt) via a traverse with instrumentation having a total mass m_2 = 4000 kg (traverse mass m_t = 3300 kg, instrumentation weight m_o = 700 kg). In the next step, the load is increased using an additional mass m_1 = 20 000 kg over 5 seconds

(c) The bolt is unloaded by raising the free-falling mass (m_1) to a predetermined height (h, in the range from approximately 1 to 12 cm) corresponding to the given load speed v_u of 0.4 to 1.2 m/s

(d) Releasing the free-falling mass (m_1 = 20 000 kg) into free fall from height h onto the traverse (m_2 = 4 000 kg).

The test result in the second step is considered to be positive if the bolt transfers the given load without suffering damage (the continuity of the material is uninterrupted), and the bolt does not protrude from the steel cylinder by more than 80% of its length.

The maximum values of the impact speed vu obtained during the test in stages 1 and 2 form the basis for the classification of the bolt into one of the impact resistance categories. These categories are shown in Table III (W1–W5). When classifying a bolt, a lower impact speed from the test results of stage 1 and 2 is selected.

During the tensile impact load test of a bolt bonded to the steel cylinder, the momentary dynamic resistance force F_d of the bolt is recorded. During this test, the maximum value F_{dmax} of the momentary dynamic resistance force F_d of the bolt is determined. Before and after the test, the length L of the bolt and the bolt geometry are measured to determine its elongation ΔL or the length of the extension from the steel cylinder ΔL_w (Figure 9).

All measurement data was recorded with a minimum test frequency of 9600 Hz. For the force measurement, strain gauges and HBM measuring amplifiers were used. Each bolt was tested according to the presented methods. If the condition of the bolts allowed, tests on the destroyed bolts (or shearing that occurred at the wire-binder or binder-concrete interface) were continued to determine their post-critical load capacity.

Results and analysis of the yielding bolt tests conducted under dynamic load conditions

In this section, selected results of the yielding bolt tests conducted at the GIG facility under dynamic load conditions using the methodology described in the previous section are presented. The study objects were yielding bolts with a nominal load-bearing capacity of 420 kN. A schematic of the bolt is shown in Figure 10.

The bolts were composed of a bundle of eight wires with a diameter of 7 mm, seven of which were located peripherally to one wire at the centre. The bolts also incorporated a cylinder liner and a nut with an M42 × 2 threading. The outer diameter of the yielding bolt was approximately 23 mm, and the length approximately 1.5 m.

Load-deflection curves of force F to elongation L of three bolts are shown in Figure 11. Undamaged wires transferred a load of 430 to 442 kN.

In a subsequent step, a test was conducted on the mechanical components of the yielding bolts under dynamic loading.

In the first stage of the examination, the bolts were found to meet the requirements of the W3 impact resistance category. The maximum dynamic resistance force F_{dmax} was approximately 420 kN. An example chart of the dynamic resistance force is illustrated in Figure 12. The abovementioned bolt was not damaged and maintained its functionality during the test at an impact speed of v_u = 0.8 m/s. After the test, it was found that only the bolt wires had protruded from the steel cylinder by approximately 80 mm. Fading vibrations of forces are visible in the graph. Their envelope is similar to a power curve.

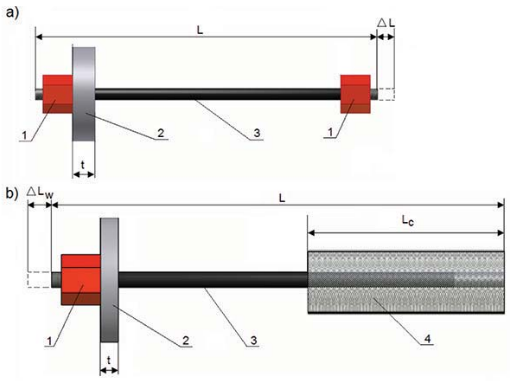


Figure 9—Scheme of the measurements performed during the test: (1) nut, (2) plate, (3) bolt, (4) steel cylinder, L=length of the bolt, ΔL=elongation of the bolt, ΔL_w=extension from the steel cylinder, L_c=length of the steel cylinder

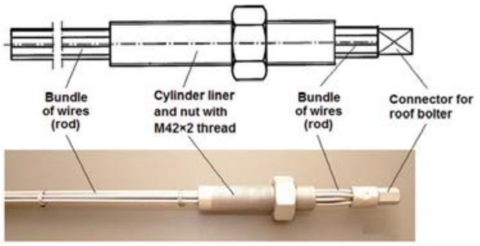


Figure 10—Mechanical construction scheme and photograph of yielding bolt (www.interram.pl)

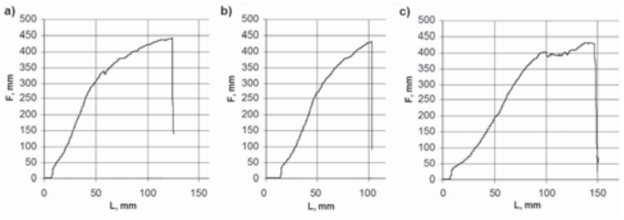


Figure 11—Load-deflection curves for three tensile tests on mechanical elements of the bolts

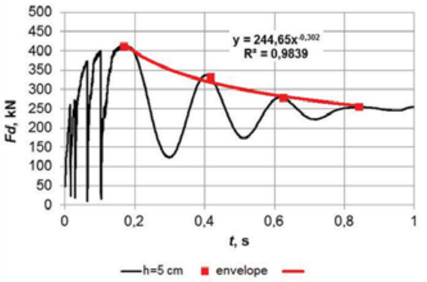


Figure 12—Dynamic resistance force (F_d) *vs* time (t) for the yielding bolt at an impact speed v_u = 0.8 m/s (h=0.05 m) - the bolt was not destroyed

Figure 13 shows an example chart of the dynamic resistance force of the bolt, which was destroyed by breaking of the wires in a wedge clamp. The clamp was located inside the cylinder liner.

In the second stage of the dynamic tests, the yielding bolts were bonded to the steel cylinder with a TSM-70K mineral cement-type binder. The characteristics of TSM-70K were determined in accordance with PN-EN 196-1: 2006. The UCS strengths after 1, 3, 7, and 28 days are shown in Figure 14. To bind the bolts inside the steel cylinder, a hole with a diameter of 32 mm was drilled.

As indicated by the graph demonstrating the strength of the TSM-70K binder, the parameters considerably exceed the requirements of the Polish standard (PN-G-15091: 1998). The Polish standards specify that the minimum UCS strength of cement and other mineral binders be 5 MPa after 3 days following mixing of the components.

An additional test (not included in the Polish standards governing the requirements) relevant to bolts used in mining (PN-G-15091: 1998, PN-G-15091: 1999) was also performed. The test consisted of pulling a bolt with a length of approximately 400 mm out of the steel cylinder with a quasi-static load (extension rate of the bolt, v, of approximately 20 mm/min). The test was performed 3 days after binding in the cylinder. The force F pulling the bolt from the steel cylinder as a function of bolt extension length L and as a function of time t is shown in Figure 15.

During this test, the mechanical components of the bolts were not damaged; however, the connection was sheared at the wire-bonder interface. This study confirmed that the anchor had a relatively high static load capacity of up to 350 kN after three days of being bonded. The greatest bearing capacity loss occurred when a bolt protruded from a cylinder a distance of approximately 220 mm.

The test results for the yielding bolts under dynamic loading (14 days after bonding) are shown in the graphs in Figures 16 and 18. The bolts were bonded to a steel cylinder with a length of approximately 400 mm. The tests were performed with an impact speed v_u of 0.6 to 0.8 m/s. The results of these tests were negative and prevented the classification of the bolts into the W3 category (they do not meet the lower W2 category). The test results 21 days after bonding are shown in Figures 19 and 20. A summary of test results and calculations is shown in Table IV.

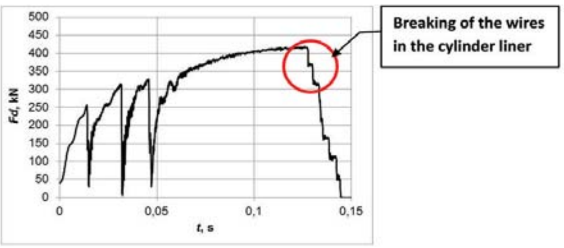


Figure 13—Dynamic resistance force (F_d) *vs* time (t) for the yielding bolt at an impact speed v_u = 0.9 m/s (h=0.07 m) – the bolt was destroyed

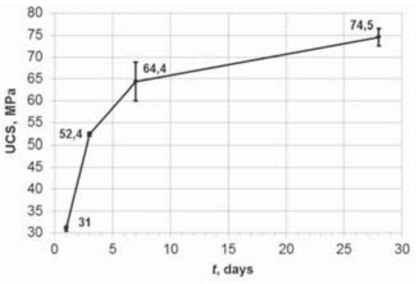


Figure 14—Uniaxial compressive strength of TSM-70K binder

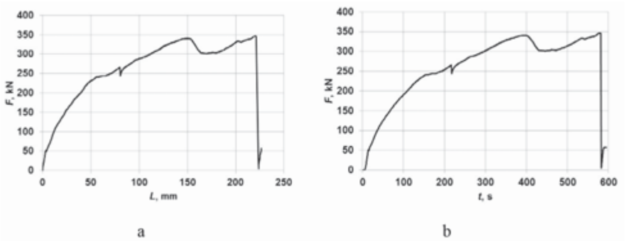


Figure 15—Graphs of force (F) used to pull the yielding bolt from the cylinder under static load (three days after being bonded within a cylinder): (a) as a function of bolt extension length (L); (b) as a function of time (t)

Based on the analysis of the graphs presented in Figures 16 and 18, it can be concluded that the wires protruded from the cylinder in each of the laboratory tests (in tests of bolts 14 days after bonding). This was caused by shearing at the wire-binder interface. The loss of adhesion between the wires and binder in the steel cylinder previously occurred at a force of F_d = 110 kN. As this process proceeded, the rod advanced in pulses from the hole in the cylinder. The test was continued until the bearing capacity of the bolt was totally lost. The rod, washer, and nut remained intact after the test.

To test the effect of the binding time of a mineral binder, various studies of bolts (21 days after the bolts were mounted to the steel cylinder) were performed. As shown in Figure 19, the bolt transferred the dynamic load without being damaged. This load was exerted by the free-falling mass released from a height of h = 0.4 m. This exceeds the requirements for bolts in the impact resistance category W2.

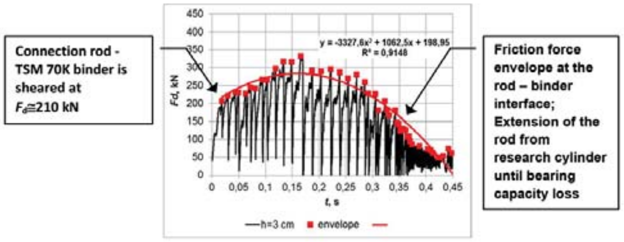


Figure 16—Graph of dynamic resistance force (F_d) *vs* time (*t*) for the yielding bolt at an impact speed v_u of 0.6 m/s (*h* = 0.03 m, 14 days after bonding) - test no. 1

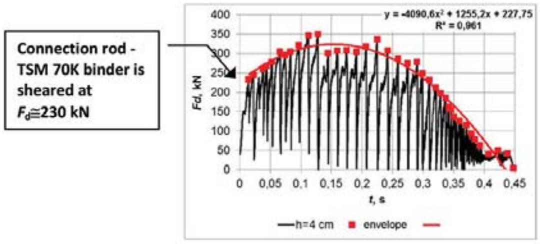


Figure 17—Graph of dynamic resistance force (F_d) *vs* time (*t*) for yielding bolt at an impact speed v_u of 0.7 m/s (*h*=0.04 m, 14 days after bonding) – test no. 2

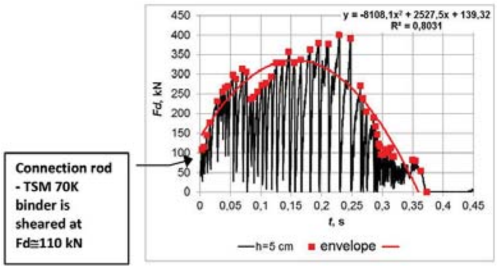


Figure 18—Graph of dynamic resistance force (F_d) *vs* time (*t*) for yielding bolt at an impact speed v_u of 0.8 m/s (*h*=0.05 m, 14 days after bonding) – test no. 3

Although the rods protruded from the cylinder (over a length of 27 mm), the bolt did not protrude from the cylinder. In comparison with studies after 14 days, the wire-binder interface transferred a load of F_d = 420.6 kN (an increase of 83% compared to sample no. 2, as shown in Figure 15; F_d = 230 kN) during the bolt test 14 days after mounting in the cylinder. The first two maximum values of the force shown in the graph (Figure 19) are related to the momentary sliding of the rod at the interface with the binder. The bolt remained able to dissipate an impact energy of E_k = 6.7 kJ. After stabilization in the hole, damping of the bolt vibrations occurred. The envelope is shown in the chart.

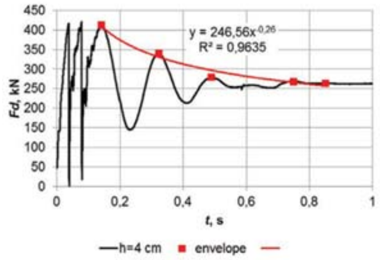


Figure 19—Graph of dynamic resistance force (F_d) *vs* time (*t*) for yielding bolt at an impact speed v_u of 0.7 m/s (*h*=0.04 m, 21 days after bonding) – test no. 4

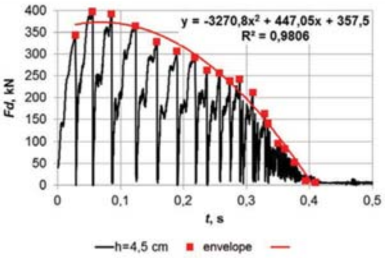


Figure 20—Graph of dynamic resistance force (F_d) *vs* time (*t*) for yielding bolt at an impact speed v_u of 0.7 m/s (*h*=0.045 m, 21 days after bonding) – test no. 5

Table IV

Yielding bolt test results in stage 2– in steel cylinder

Test no.	Number of days after bonding the bolt to a cylinder	*h* (m)	F_{dmax} (kN)	F_t (kN)	v_u (m/s)	E_k (kJ)	Visual inspection after the experiment
1	14	0.03	332.5	148.7	0.64	5.1	No damage to the mechanical parts of the bolt. Wires protruded fully from the cylinder. Shearing at wire-binder interface.
2	14	0.04	349.8	162.9	0.74	6.7	
3	14	0.05	401.2	169.1	0.83	8.4	
4	21	0.04	420.6	302.3	0.74	6.7	No damage to the mechanical parts of the bolt. Wires protruded from the cylinder to a length of 27 mm.
5	21	0.045	397.9	174.6	0.81	7.6	No damage to the mechanical parts of the bolt. Wires protruded fully from the cylinder Shearing at wire-binder interface

h - the fall height of the impact mass, m
F_{dmax} - the maximum dynamic resistance force, kN
F_t - the average frisction force, kN
v_u – the impact speed, m/s
E_k – the kinetic energy, kJ.

During the tests (classifying the bolt in the W3 category; v_u = 0.8 m/s), the bolts subject to an impact speed of 0.7 m/s protruded from the steel cylinder. The bolt did not transfer the load (without being damaged), as indicated in the graph in Figure 20.

Figures 21 and 22 present examples of the yielding bolts after the tests.

Under dynamic loads resulting from an impact at speeds v_u in the range of 0.6 to 0.8 m/s, none of the mechanical components of the yielding bolt were damaged, indicating that the weakest component was the wire-binder interface. Thus, the length of the bonding in the hole must be increased, ensuring full use of the bearing capacity of the bolt. A significant increase in the load-bearing capacity of the bolt can also be obtained by extending the setting time, which was confirmed by the performed tests (21 days after bonding).

The study also shows that, despite the shearing of the connection between the rod and the binder, the bolt did not completely lose its bearing capacity and continued to function on the principle of frictional contact in the hole until complete extension of the rod from the hole. During this frictional contact, the resistance was observed to vary in pulses and decreased to zero. Despite the relatively short cylinders (with a length of approximately 400 mm) in the tests, maximum values of the dynamic resistance forces F_{dmax} in the range of 330.0 to 420.6 kN were obtained. This is important for the bolts' post-critical performance, *i.e.*, after shearing at the wire-binder interface.

Analysis of the yielding bolt performance during its extension out of the steel cylinder (after shearing at the rod-binder interface) demonstrated that the friction force between the rod and the wall of the cylinder hole was nonlinear. This was assumed by Gaudreau, Aubertin, and Simon (2004). The shape of the frictional force envelope is similar to a power function. In Figures 15 and 19, the protrusion process of the rod from the cylinders consists of impulse forces. These forces correspond to the rods slipping until the test is halted or until the rods extend totally out of the cylinder. The charts also show the equations of the envelopes of the friction force F_t. The differences in performance of the yielding bolt after 14 and 21 days can be observed.

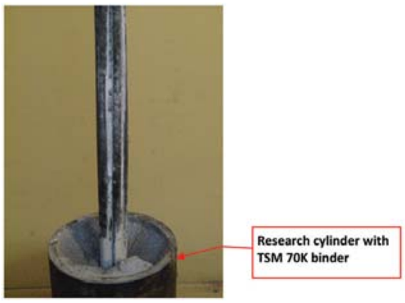


Figure 21—Bolt rod protruding from the cylinder after the test

Figure 22—Yielding bolt after the test (without damage) as a threaded cylinder liner and nut

Summary

To select appropriate mine working supports for conditions that may include exposure to dynamic phenomena, the performance of such supports must be determined under dynamic conditions. One of the commonly used methods of support assessment under dynamic loading is laboratory testing using a free-falling mass impacting a test object. This article described a methodology for the laboratory testing of rockbolts developed by and employed at the GIG for the study of bolt behaviour under dynamic load conditions. The parameters of the laboratory tests were defined by considering the estimated speed of the rock mass during rock bumps and tremors in Polish coal mines. In the GIG test facilities, it is possible to dynamically load the tested bolts using the momentum of a large freely moving mass (20 000 kg) applied to bolts at speeds of up to 1.2 m/s. In Polish underground coal mines, the primary support of workings, erected during development, is steel arches. Under difficult geo-mining conditions, the steel arch and surrounding rock mass are reinforced using bolts. During the exploitation of coal seams, severe rockbursts and tremors occur each year. The occurrence of these phenomena means that, prior to application of different supports in mine workings, it is necessary to assess their bearing capacity under dynamic load. Such assessment is possible with the methodology described in this paper, as confirmed by test results of yielding bolts.

Given past experience, bolts with a minimum category of impact resistance of W3 are recommended for use in Polish underground coal mines.

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