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

by A. Pytlik*, S. Prusek*, and W. Masny*

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/m² 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).

* Central Mining Institute, Katowice, Poland.
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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 (Kidybiniski, 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 retrofitted with single entries (101 faces with natural roof caving into the gob and six with hydraulic backfilling). The average depth of the cover was 715 m; however, increasingly more collieries are exploiting coal deposits 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 (Patyniska, 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 (Patyniska, 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 5x2x6 m (height x width x length) through the direct impact of a 1000–20 000 kg freely moving mass. The maximum impact energy is 500 kJ, and the initial
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**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)

<table>
<thead>
<tr>
<th>Year</th>
<th>Total production (Mt)</th>
<th>Extraction from seams located in rockburst areas (% to general)</th>
<th>Accident ratio (accidents/extraction)</th>
<th>No. of rockbursts</th>
<th>Rockburst accidents</th>
<th>Consequence in mine workings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fatal</td>
<td>Other</td>
<td>Destroyed after rock fall (m)</td>
<td>Damaged mine workings (m)</td>
</tr>
<tr>
<td>2003</td>
<td>100.40</td>
<td>41.8</td>
<td>0.18</td>
<td>4</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>2004</td>
<td>96.99</td>
<td>39.2</td>
<td>0.11</td>
<td>3</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>2005</td>
<td>99.50</td>
<td>41.0(1)</td>
<td>0.13</td>
<td>3</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>2006</td>
<td>94.50</td>
<td>42.15</td>
<td>0.25</td>
<td>4</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>2007</td>
<td>87.40</td>
<td>44.6(1)</td>
<td>0.11</td>
<td>3</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>2008</td>
<td>83.60</td>
<td>41.9(2)</td>
<td>0.31</td>
<td>5</td>
<td>0</td>
<td>26</td>
</tr>
<tr>
<td>2009</td>
<td>77.5</td>
<td>34.3(2)</td>
<td>0.06</td>
<td>1</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>2010</td>
<td>76.1</td>
<td>35.8(3)</td>
<td>0.18</td>
<td>2</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>2011</td>
<td>75.50</td>
<td>34.2(4)</td>
<td>0.08</td>
<td>4</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>2012</td>
<td>79.20</td>
<td>37.60</td>
<td>0.04</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2013</td>
<td>76.47</td>
<td>36.90</td>
<td>0.07</td>
<td>1</td>
<td>0</td>
<td>5</td>
</tr>
</tbody>
</table>

(1) Approximate data

**Figure 2**—Damaged mine workings after rockbursts. (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

<table>
<thead>
<tr>
<th>Bolt type</th>
<th>Diameter of bolt (mm)</th>
<th>Length of bolt (m)</th>
<th>Load-bearing capacity (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yielding bolts</td>
<td>20</td>
<td>30</td>
<td>3.0</td>
</tr>
<tr>
<td>Rebar bolts (rigid)</td>
<td>16</td>
<td>40</td>
<td>1.0</td>
</tr>
<tr>
<td>Injection bolts</td>
<td>20</td>
<td>43</td>
<td>1.3</td>
</tr>
<tr>
<td>Cuttable bolts</td>
<td>25</td>
<td>41</td>
<td>3.0</td>
</tr>
<tr>
<td>Expansion shell bolts</td>
<td>20</td>
<td>40</td>
<td>0.8</td>
</tr>
<tr>
<td>Cable bolts</td>
<td>18</td>
<td>18</td>
<td>6.0</td>
</tr>
</tbody>
</table>
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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 \( m_1 \). The main dynamic load is exerted by the impact of a free-falling mass \( m_2 \) from a height \( h \). During the test, the loading speed \( v_a \) depends on the height \( h \). The impact speed \( v_a \) is calculated under the assumption of a plastic collision of the masses \( m_1 \) and \( m_2 \). The speed \( v_a \) of the free-falling mass from the height \( h \) at the traverse at the moment of impact is calculated from

\[
v_a = \sqrt{2gh}
\]

where

\( h \) – height, m
\( g \) – acceleration due to gravity, m/s\(^2\).

The speed \( v_a \) 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 \( v_a \) of the joined masses \( m_1 \) and \( m_2 \), the principle of conservation of momentum is used:

\[
m_1 v_a = (m_1 + m_2) v_s
\]

from which we obtain

\[
v_a = \frac{m_1}{m_1 + m_2} v_s
\]

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 \( v_s \) 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 \( m_2 \):

\[
E_k = \frac{1}{2} (m_1 + m_2) v_s^2
\]

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

\[
E_k = \frac{m_1^2}{(m_1 + m_2)} g \cdot h
\]

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 \( F_f \) from the start of the bolt protrusion from the cylinder until the end of the feed of the bolt is calculated as follows:

\[
F_f = \frac{1}{t_2 - t_1} \int F_f dt
\]

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 (Dubinski 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 \( \geq 0.4 \) 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, \( v_{ppv} \), 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
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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, \( v_r \), 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 a pre-tension of the bolt by a traverse with instrumentation weight \( m_t = 3300 \text{ kg} \), instrumentation weight \( m_w = 700 \text{ kg} \). In the next step, the load is increased by an additional mass \( m_t = 20000 \text{ kg} \) 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)

Table III

<table>
<thead>
<tr>
<th>Category</th>
<th>( v_r ) (m/s)</th>
<th>( h ) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>0.4</td>
<td>1.3</td>
</tr>
<tr>
<td>W2</td>
<td>0.6</td>
<td>3.0</td>
</tr>
<tr>
<td>W3</td>
<td>0.8</td>
<td>5.0</td>
</tr>
<tr>
<td>W4</td>
<td>1.0</td>
<td>8.0</td>
</tr>
<tr>
<td>W5</td>
<td>1.2</td>
<td>12.0</td>
</tr>
</tbody>
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<td>5.0</td>
</tr>
<tr>
<td>W4</td>
<td>1.0</td>
<td>8.0</td>
</tr>
<tr>
<td>W5</td>
<td>1.2</td>
<td>12.0</td>
</tr>
</tbody>
</table>

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 \( m_1 = 4000 \text{ kg} \), (traverse mass \( m_w = 3300 \text{ kg} \), instrumentation weight \( m_w = 700 \text{ kg} \). In the next step, the load is increased by an additional mass \( m_t = 20000 \text{ kg} \) 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 \( m_t \) to a predetermined height \( h \) (in the range from approximately 1 to 12 cm) corresponding to the given load speed \( v_r \) of 0.4 to 1.2 m/s
(d) Releasing the free-falling mass (with \( m_t = 20000 \text{ kg} \) into free fall from a height \( h \) above the traverse \( m_t = 4000 \text{ kg} \)).

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 its functionality).

During the bolt test, the instantaneous value of the dynamic resistance force \( F_d \) is recorded. From the obtained data, a maximum value \( F_{d_{max}} \) is determined. Before and after the test, the length of the bolt \( L \) is measured. This enables the elongation \( \Delta L \) 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
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(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 $m_1 = 3500$ kg, instrumentation weight $m_0 = 700$ kg). In the next step, the load is increased using an additional mass $m_1 = 20000$ 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 ($m_1 = 20000$ kg) into free fall from height $h$ onto the traverse ($m_2 = 4000$ 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 $v_u$ 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 $\Delta L$ or the length of the extension from the steel cylinder $\Delta L_e$ (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 11—Load-deflection curves for three tensile tests on mechanical elements of the bolts

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

Figure 13—Dynamic resistance force ($P_d$) vs time ($t$) for the yielding bolt at an impact speed $v_i = 0.9$ 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 ($x$); (b) as a function of time ($t$) with a length of approximately 400 mm. The tests were performed with an impact speed $v_i$ 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.

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 $P_g = 110$ 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.
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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 \( F_d = 420.6 \text{ kN} \) (an increase of 83% compared to sample no. 2, as shown in Figure 15; \( F_d = 230 \text{ kN} \)) 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 \( E_k = 6.7 \text{ kJ} \). After stabilization in the hole, damping of the bolt vibrations occurred. The envelope is shown in the chart.

Table IV
Yielding bolt test results in stage 2— in steel cylinder

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

\( h \) - the fall height of the impact mass, m
\( F_{\text{av}} \) - the maximum dynamic resistance force, kN
\( F_r \) - the average friction force, kN
\( v_r \) - the impact speed, m/s
\( E_k \) - the kinetic energy, kJ.
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During the tests (classifying the bolt in the W3 category; \( v_p = 0.8 \text{ m/s} \)), 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 \( v_p \) 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 \( F_p \). The differences in performance of the yielding bolt after 14 and 21 days can be observed.

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.

Acknowledgements

This article presents a brief summary of work conducted by the Central Mining Institute under the project Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future. The project is implemented under the Seventh Framework Programme of the European Union.

References


