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COMPARATIVE BENCH TESTING OF STEEL ARCH SUPPORT SYSTEMS WITH AND WITHOUT ROCK BOLT REINFORCEMENTS

STANOWISKOWE BADANIA PORÓWNAWCZE OBUDOWY PODPOROWEJ I PODPOROWO-KOTWIOWEJ

The mining of hard coal deposits at increasingly greater depth leads to an increase in hazards related to the loss of stability of steel arch supports as a result of excessive static and dynamic loads. Camber beam reinforcement via rockbolting is often utilised in order to improve the stability of the yielding steel arch support.

This article presents the results of comparative bench tests of the ŁP10/V36-type steel arch support, tested with and without reinforcement by means of self-drilling bolts with drunken R25 threads, using short joists formed from V32 and V25 sections. It also presents the results of comparative tests of the ŁPP10/4/V29/I-type steel arch support, tested with and without reinforcement by means of rock bolts with trapezoidal Tr22/13 threads, using short joists formed from V25 sections. The obtained test results, in the form of load courses and work values of the steel arch and mixed (arches and rock bolts) support systems, demonstrate that the utilisation of mixed support may significantly improve the stability of workings, particularly immediately after they are driven. A mixed support system quickly achieves its maximum load capacity together with a significant increase in its work value. It may thus prevent the stratification of the rocks surrounding the working, and therefore better utilise the self-supporting capacity of the rock mass. As evidenced by the test results, the mixed support work may be as much as 3.5 times as great compared to the steel arch support at the beginning of the height reduction process initiated by loading – i.e. until its reduction by a presupposed value of 100 mm.

Keywords: yielding steel arch support; rockbolting support system; mixed support; support work value; support load capacity

Eksploatacja pokładów węgla kamiennego na coraz większych głębokościach powoduje wzrost zagrożeń związanych z utratą stateczności podporowej obudowy górniczej w wyniku nadmiernych obciążeń statycznych i dynamicznych. W celu poprawy stateczności podatnych odrzwi obudowy podporowej często stosuje wzmocnienie odrzwi poprzez przykotwienie łuku stropnicowego.

W artykule przedstawiono wyniki stanowiskowych badań porównawczych odrzwiowej obudowy podporowej typu ŁP10/V36, badanej bez wzmocnienia oraz ze wzmocnieniem za pomocą kotwi samo-

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wiercących z gwintem falistym R25, przy użyciu krótkich podciągów wykonanych z kształtownika V32 oraz V25. Przedstawiono również wyniki badań porównawczych odrzwiowej obudowy podporowej typu ŁPP10/4/V29/I, badanej bez wzmocnienia oraz ze wzmocnieniem za pomocą kotwi z gwintem trapezowym Tr22/13, przy użyciu krótkich podciągów wykonanych z kształtownika V25.

Uzyskane wyniki badań w postaci przebiegów obciążania oraz wartości pracy obudowy podporowej i podporowo-kotwiowej wykazują, że stosowanie obudowy podporowo-kotwiowej może znacząco poprawić stateczność wyrobiska górniczego szczególnie zaraz po jego wydrążeniu. Dzięki temu, że obudowa podporowo-kotwiowa szybko uzyskuje swoją maksymalną nośność przy znaczącym wzroście wartości pracy może zapobiegać rozwarstwianiu skał wokół wyrobiska, a przez to lepiej wykorzystać samonośność górotworu. Jak wykazują wyniki badań, praca W obudowy podporowo-kotwiowej może być nawet ponad 3.5-krotnie większa od obudowy podporowej na początku procesu jej obniżania pod wpływem obciążenia – to znaczy do czasu jej obniżenia o umowną wartość 100 mm.

Słowa kluczowe: podatna obudowa podporowa, obudowa kotwiowa, obudowa podporowo-kotwiowa, wartość pracy obudowy, nośność obudowy

1. Introduction

The basic types of gallery working support systems in Polish hard coal mines are:

- steel arch support (DIN 21530-4:2016-09; PN-G-15000-05:1992; PN-G-15022:2018-11; UNE 22725:2007),
- rockbolting support systems (ASTM F432-13:2013; BS 7861-1:2007; DIN 21521-2:1993-02; PN-G-15092:1999),
- mixed support, e.g. with steel arches and rock bolts.

The steel arch support (passive) sustains the weight of the rocks in the fractured zone around the working (Cała et al., 2001), whereas the rockbolting support system (active) reinforces the natural self-supporting capacity of the rock mass surrounding the working. Yielding steel arch support (Jacobi, 1981; Majcherczyk et al., 2014; Podjadtke et al., 2008; Turek, 2010; Turek et al., 2015) and yielding rockbolting support systems (Cała et al., 2001; Sun et al., 2018) are commonly used in difficult geological and mining conditions. These conditions are related to the occurrence of significant static and dynamic loads, which are accompanied by major rock mass deformations, and are also associated with high rock mass stress (Ptáček et al., 2017). The testing of the steel arch and rockbolting support system element resistance to dynamic loads was conducted at the Central Mining Institute's test facility (located in Łaziska Górne, Poland) by means of the dynamic impact drop test (Pytlik & Stoiński, 2006; Pytlik et al., 2016; Pytlik, 2019). Currently, the most commonly employed type of yielding steel arch support is a support system with frames constructed from overlapping steel arches connected by shackles. The yield of the steel frame is achieved by means of sliding joints constructed from sections (e.g. V or TH-type), which slip after a certain value of the friction force is exceeded; this value is primarily dependent on the type of shackles and the torque of the shackle screw nuts (Brodny, 2012a, 2012b; Podjadtke et al., 2008; Pytlik, 2001, 2002; Rotkegel, 2013). The necessity to mine hard coal deposits at increasingly greater depth leads to an increase in hazards related to the loss of steel arch support stability as a result of excessive static and dynamic loads. This particularly concerns top and bottom roads as well as significantly large workings (e.g. longwall development). Yielding steel arch support frame reinforcement is often performed in such situations by means of rockbolting (mixed support with arches and rock bolts). This method of support frame reinforcement has been widely utilised in German hard coal mining (Jacobi, 1981; Das kleine Bergbaulexikon, 1988), and is currently also employed in Polish and Czech mines in the Upper Silesian Coal Basin (Ptáček et al., 2017). Support frame rockbolting is often utilised to secure the longwall entry – at the intersection of the longwall with the gallery. A similar situation occurs during longwall extraction (Nierobisz, 2006), where large steel arch support systems require additional reinforcement. Rockbolting of the support frame increases its load capacity (Turek, 2010, 2012; Turek et al., 2015), which also makes it possible to increase its spacing and to limit the number of utilised reinforcement elements, i.e. props and joists, that limit the throughput of the working. This leads to an increase in work safety and is also important from the economic perspective, as the decrease in the number of support frames results in significant savings. The use of rockbolting support systems results in rock mass reinforcement and, consequently, a decrease in the loading of the steel arch support (Daniłowicz, 2000; Daniłowicz & Skrzyński, 2003; Daniłowicz et al., 2006).

Recent data from Polish hard coal mines indicates (Turek et al., 2015) that in 2012 mixed support systems were the most commonly employed type of gallery working support systems utilising rock bolts. The mixed support consists of yielding steel arch or straight frame sets combined with rock bolts (e.g. directly via openings in the frame sets or indirectly via short joists). As the study showed, as much as 76.4% of the total metric area of the rock bolt-reinforced gallery workings was secured by means of mixed support systems. Polish hard coal mine experience (Turek et al., 2012) confirms the efficiency of utilising mixed support systems in order to limit gallery working deformation.

Due to the different nature of the interaction of the yielding steel arch support and the rock bolts with the rock mass (Turek, 2010), and due to the complexity of this interaction (Cała et al., 2001), an attempt was made at the Central Mining Institute to compare the courses of the support load F as a function of the support height reduction ΔH. This article presents the results of comparative bench tests of the ŁP10/V36-type steel arch support, tested with and without reinforcement by means of self-drilling bolts with external drunken R25 threads (ISO 10208:1991). The ŁP10/V36 support frame reinforcement was accomplished by means of a short joist constructed from a V32 or V25 section, coupled to the R25 self-drilling bolts. This article also presents the results of comparative bench tests of the ŁPP10/4/V29/I-type steel arch support, tested with and without reinforcement by means of bolt rods with an outer nominal diameter of 22 mm and external trapezoidal Tr22/13 threads. The ŁPP10/4/V29/I support frame reinforcement was accomplished by means of a short joist constructed from a V25 section, coupled to the bolts with Tr22/13 threads. The newly developed test methodology and facility (Pytlik, 2017) of the Central Mining Institute (located in Katowice, Poland) make it possible to conduct full scale testing of yielding frames, with the inclusion of the deformability of both the bolts and the intermediate elements (e.g. joists, lifting hooks and shackles, etc.). The test results may be used by the manufacturers of steel arch and rockbolting support system elements, in order to optimise their constructions, as well as by mine support designers.

2. Test methodology and test facility structure

The comparative bench tests of steel arch and mixed support systems were conducted at the test facility of the Central Mining Institute in Katowice, displayed as a diagram in Fig. 1. The active and passive forces were exerted on the support by means of hydraulic actuators.

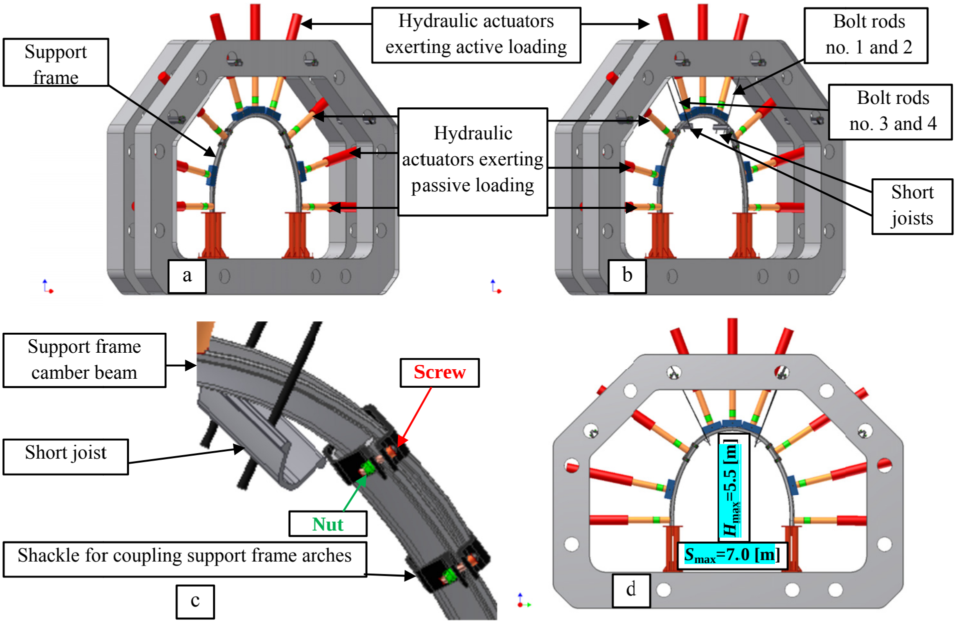


Fig. 1. Facility diagram for testing support systems: a – steel arch; b – mixed; c – short joist with two bolts in the area of the support frame joint; d – maximum support frame dimensions

A steel support frame without reinforcement was subjected to testing during the first stage of the test. The test methodology was based on an applicable standard (PN-G-15000-05:1992) that defines the support frame loading diagram. During the second stage, the same frame set was reinforced with four rock bolts as per Fig. 1 and subjected to standard loading as per Fig. 2, according to the applicable standard (PN-G-15000-05:1992). The work and load capacity of the support and of the separate support elements were subjected to comparative analysis.

The comparative tests were conducted on three-element ŁP10/V36-type frames (constructed from V36 sections, grade of steel S550W) and four-element ŁPP10/4/V29/I-type frames (constructed from V29 sections, grade of steel S560W), tested with and without reinforcement by means of rock bolts.

The three-element ŁP10/V36-type frames were reinforced using self-drilling bolts with external drunken R25 threads (ISO 10208:1991). The ŁP10/V36 support frame reinforcement was accomplished by means of two short joists (constructed from V32 or V25 sections) coupled to the self-drilling bolts with R25 threads.

The four-element ŁPP10/4/V29/I-type frames were reinforced using bolts with an outer nominal diameter of 22 mm and imperfect rolled screw trapezoidal Tr22/13 threads. The ŁPP10/4/V29/I support frame reinforcement was accomplished by means of two short joists (constructed from V25 sections) coupled to the bolts with Tr22/13 threads.

The joists had two openings (Fig. 1c), spaced 350 mm apart, intended for the installation of the bolt rods. The V sections were constructed in accordance with applicable standards (PN-H-93441-1:2013-12; PN-H-93441-3:2004), the arches in accordance with standard PN-G-15000-03:1993 and the shackles in accordance with standard PN-G-15011:2011.

Detailed support frame loading diagrams are presented in Fig. 2.

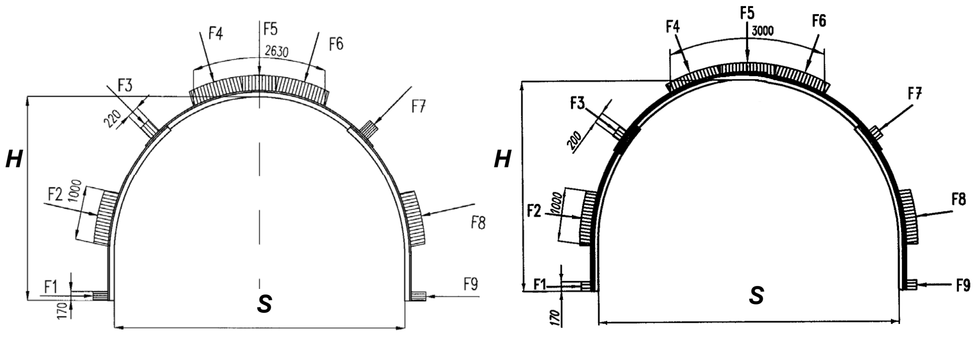


Fig. 2. Loading diagrams for ŁP10/V36 (a) and ŁPP10/4/V29/I (b) frames during bench testing (F_4, F_5, F_6 – active forces, F_1, F_2, F_3, F_7, F_8, F_9 – passive forces)

The tests of basic frames and frames with bolt reinforcement are conducted until:

A. a total height reduction ΔH by 20% of the initial frame height is achieved as a result of joint yield,
B. the frame joints jam,
C. any support element fails.

The test facility was equipped with a QUANTUM^X measuring amplifier connected to strain gauge pressure sensors installed in the hydraulic actuators, and to a displacement sensor measuring the support frame height reduction. The hydraulic actuators exerted active loading on the support frame. The measurements were conducted with a sampling frequency of f_p = 10÷50 Hz.

In order to compare the two types of support, the value of the support work W is calculated by means of numerical integration (trapezoidal rule) of the measurement courses $F = f(H)$, from the following formula:

$$W = \int_{H_1}^{H_2} F(H)\,dH\text{, kJ} \tag{1}$$

where: F – measured loading force, kN; H – support frame height reduction ranging from $H_1 = 0$ to a value of H_2 achieved by the conclusion of the test, m.

The maximum load capacity $F_{b\max}$ of the bolts used during the mixed support tests is also inspected before testing, while the total work W_b, required to achieve their rupture during the tensile test is determined using the following formula:

$$W_b = \int_{L_{b1}}^{L_{b2}} F_b(L_b)\,dL_b\text{, kJ} \tag{2}$$

where: F_b – measured loading force, kN; L_b – bolt elongation from the initial value $L_{b1} = 0$ until the value at rupture L_{b2}, m.

The bending work W_V of the V section is also determined from the following formula:

$$W_V = \int_{D_{V1}}^{D_{V2}} F_V(D)\,dD, \text{ kJ} \tag{3}$$

where: F_V – bending force [kN] exerted on a segment of the section as per the diagram in Fig. 3:

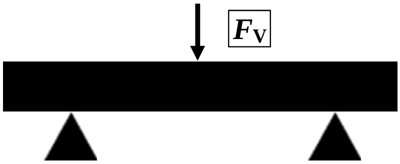


Fig. 3. V section bending diagram

D – V section bend from the initial value $D_{V1} = 0$ until the value at test conclusion D_{V2}, m.

The section bend courses also present the dependence of the section bending moment M_g as a function of the section bending rate ΔD.

3. Comparative tests of steel arch and mixed support systems based on ŁP10/V36-type frames

The ŁP10/V36 frames had an initial height of $H = 3770$ mm and width of $S = 5500$ mm. Due to their very high strength parameters and increased resistance to corrosion, frames of this type are intended for use under particularly difficult geological and mining conditions. The tests utilised SDOw32/34/36 shackles, also with reinforced constructions, whereas the shackle screws (class 10.9) in the joints were tightened with a torque of $M_d = 400$ Nm.

Self-drilling bolts with outer R25 threads were used to reinforce the support frame camber. In addition to their high load capacity, which exceeds 200 kN, the bolts also provide the possibility to perform injections into the rock mass surrounding the working by means of high-strength bonding agents.

Steel arch and rockbolting support systems with very high strength parameters were selected for the tests in order to inspect their resultant load capacity and work, as these parameters are highly significant from the perspective of support utilisation in deep mines.

The testing of two bolts under tensile loading was conducted according to the diagram presented in Fig. 4 until their rupture.

The R25 bolt load capacity tests, whose courses are presented in Fig. 5, confirmed the high load capacity of the bolts, which according to the manufacturer's catalogue data should amount to at least 200 kN. The total bolt length was 3 m. During testing, the bolts had nuts mounted on both ends. The initial bolt length between the nuts was $L_B = 2.6$ m.

The maximum force during the two tests was $F_{b\max} = 217$ kN, whereas the value of bolt work until failure varied (as a result of differences in bolt rod elongation until rupture) and amounted to:

– test no. 1 – $W_b = 12.6$ kJ,
– test no. 2 – $W_b = 9.5$ kJ.

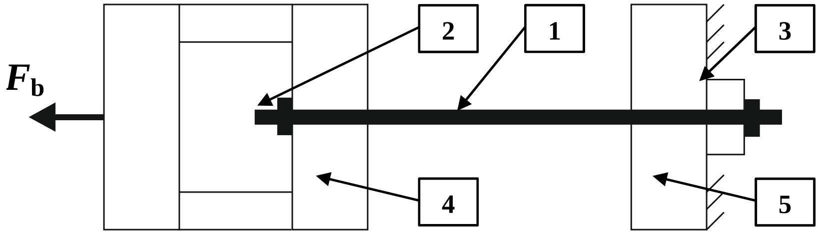


Fig. 4. Bolt rod tensile loading diagram.
1 – bolt rod; 2 – nut; 3 – strain gauge force sensor; 4 – tensile testing machine mobile element; 5 – tensile testing machine immobile element

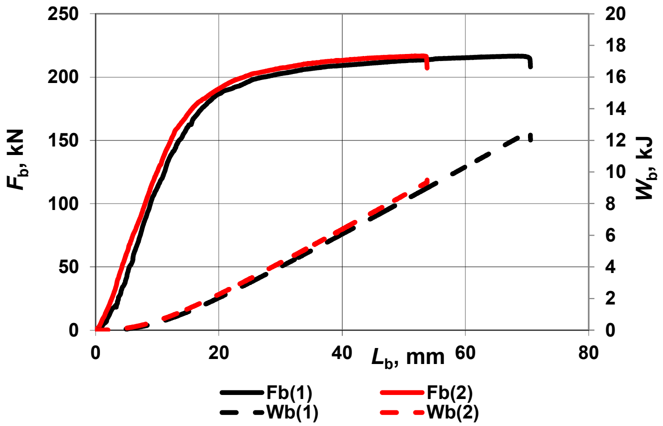
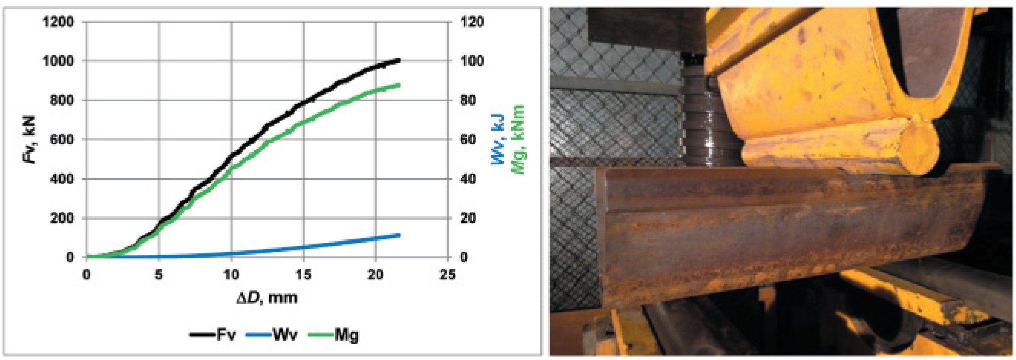


Fig. 5. Chart of loading force F_b and work W_b dependence as a function of elongation L_b of the R25 bolt

The results of V section bend tests are presented in Fig. 6 and 7.



a b

Fig. 6. V32 section bending course: a – chart of loading force F_v dependence as a function of bending ΔD; b – slight section deformation after the test

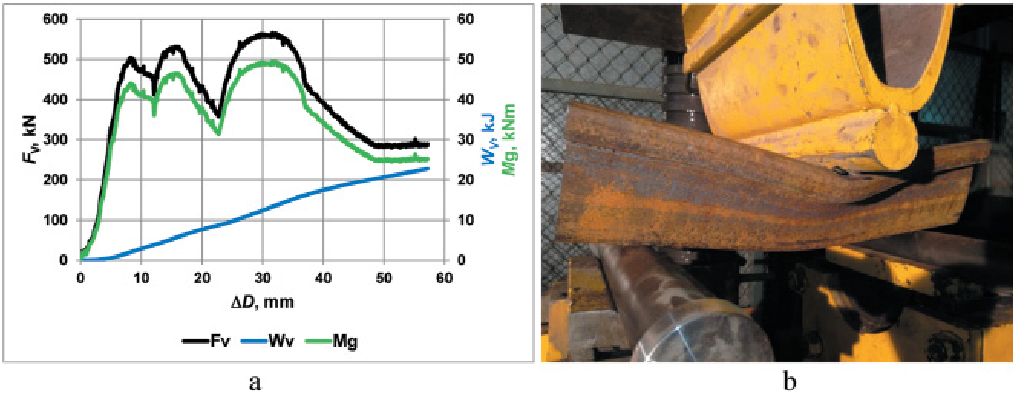


Fig. 7. V25 section bending course: a – chart of loading force F_v dependence as a function of bending ΔD; b – significant section deformation after the test

The maximum force bending the V32 section ($F_{V\max}$ = 1004 kN) was approx. 80% greater than the maximum force bending the V25 section ($F_{v\max}$ = 566 kN). When the sections reached a point where they were bent by a value of up to 20 mm, the bending work was slightly greater for the V32 section and amounted to approx. 9 kJ, whereas for the V25 section the bending force was approx. 8 kJ, at which the V25 section had already undergone major deformations (Fig. 7b). The section bend test was interrupted at a value of approx. 1000 kN (with a slight deformation of approx. 20 mm, as presented in Fig. 6b), as that value significantly exceeded the load capacity of the bolts utilised during the tests. Since the short joists constructed from V sections are used to couple the bolts to the yielding support frame, the load characteristics as a function of deformation of all the support elements are very important. In a situation where a yielding frame and rock bolts that constitute a rigid support interact as part of a single support system, it is particularly important to select an adequate joist constructed from a V section. This must be done in order to ensure the optimal interaction of both the support types through the maximum utilisation of their load capacity and deformation.

Fig. 8 presents a chart of loading force F dependence as a function of the ŁP10/V36 support frame height reduction ΔH, which was tested after the joints were made rigid in order to determine the maximum frame load capacity resulting from the strength parameters of the V36 section formed from S550W steel.

Fig. 9 presents a chart of loading force F dependence as a function of the ŁP10/V36 support frame height reduction ΔH, tested in a yielding state.

At the initial stage of its operation the support yields at a relatively low force of approx. 400 kN, while the slight yields (visible in the chart in the form of force peaks) range from several to around a dozen mm. During the final stage of frame operation, an increase in support load capacity resulting from the stiffening of the joints was observed, which led to an increase in the load capacity from 800 kN to 1000 kN and to yields in the joint of up to several dozen mm. However, it must be stressed that the increase in support load capacity occurs only at a very significant height reduction of the support frame, by approx. 600 mm. In practice, a working like this would require relining. Comparing the rigid and yielding support loading courses, as depicted on charts in Fig. 8 and 9, a difference can be observed in the work and load capacity

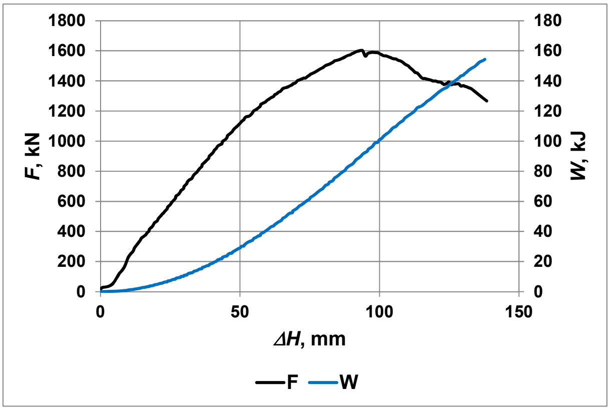


Fig. 8. Course of loading force F as a function of height reduction ΔH of an ŁP10/V36 support frame in rigid state

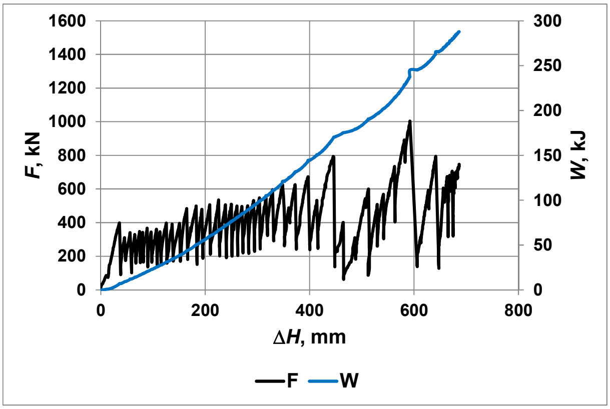
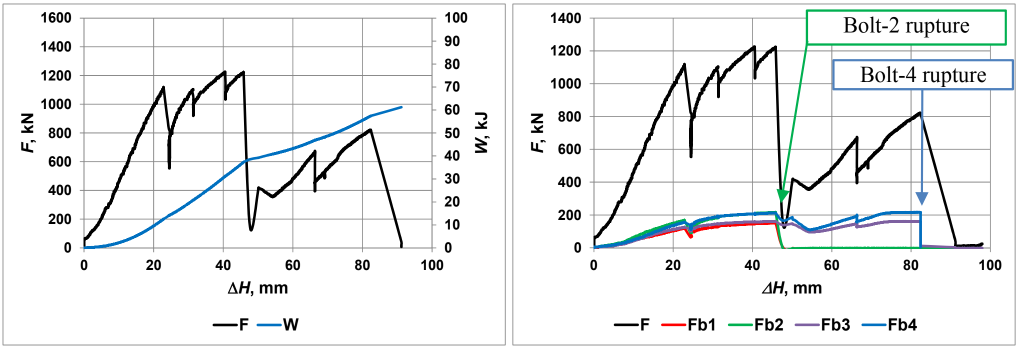


Fig. 9. Course of loading force F as a function of height reduction ΔH of an ŁP10/V36 support frame in yielding state

of both the support types. In practice, attempts are made to increase the yielding support frame shackle screw tightening torques with the aim of maximising the average support load capacity obtained during yielding, while simultaneously retaining the further ability of the joints to slide. This makes it possible to better utilise the high strength of the steel used to construct the support frame arches.

Fig. 10 presents the courses of loading force F as a function of the height reduction ΔH of ŁP10/V36 support frames tested in yielding state and reinforced by means of four R25 bolts, according to the diagram displayed in Fig. 1b. The test also utilised short joists constructed from V32 sections and formed from S480W steel.

Points of significant joint yields were marked on the chart. These joint yields resulted in a loss of tension in the bolts. Rapid displacements of the short joists along the support frame section were also observed during testing, which even resulted in visible sparking.



a b

Fig. 10. Courses of: a – loading force F and work W as a function of height reduction ΔH of ŁP10/V36 support frames in yielding state, reinforced with four R25 bolts coupled to a short joist constructed from a V32 section; b – the force loading the frames and bolts

Before bolt rupture, the support operated in a symmetric arrangement (two bolts on each side of the active actuator F_5). Following the rupture of bolt-2, the support operated in an asymmetric arrangement – i.e. the camber was reinforced only in the area of the joint adjacent to bolt-2. Such a situation resulted in the occurrence of support frame yield only in the joint adjacent to the ruptured bolt-2, while the yield value amounted to several dozen mm. The test was interrupted following the rupture of bolt-4. No deformations of the joists constructed from V32 sections were observed after the test.

Fig. 11 presents charts of loading force F dependence as a function of the height reduction ΔH of the ŁP10/V36 support frame, tested in yielding state and reinforced with four R25 bolts. The test also utilised short joists constructed from V25 sections, formed from 34GJ steel.

Comparing the support load courses depicted on charts in Fig. 10 and 11, it can be observed that the same support frames reinforced with R25 bolts exhibit different maximum load capacity and work, depending on the utilised joist. As the V25 section is characterised by a greater

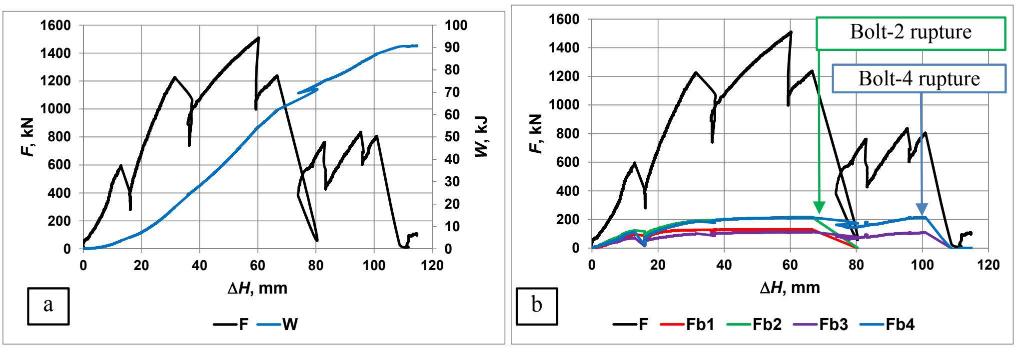


Fig. 11. Courses of: a – loading force F and work W as a function of height reduction ΔH of ŁP10/V36 support frames in yielding state, reinforced with four R25 bolts coupled to a short joist constructed from a V25 section; b – the force loading the frames and bolts

yield than the V36 section, the load exerted on the frame and bolts is more uniform, which has a beneficial influence on the increase in support work and load capacity.

Similarly to the previous mixed support test, prior to bolt rupture the support operated in a symmetric arrangement. Following the rupture of bolt-2 the support operated in an asymmetric arrangement, which resulted in the occurrence of support frame yield only in the joint adjacent to the ruptured bolt-2, and the yield value also amounted to several dozen mm. The test was interrupted following the rupture of bolt-4. Significant deformations of the joists constructed from V25 sections were observed after the test. Typical bolt rod failure is presented in Fig. 12.

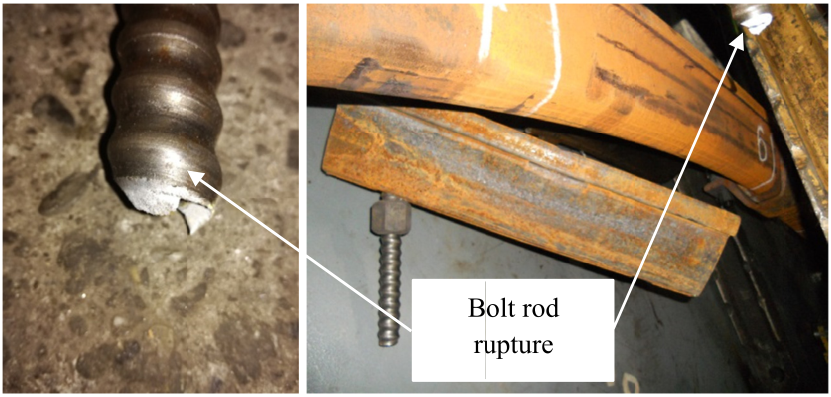


Fig. 12. Post-test bolt rod failure: a, b – bolt rod rupture at the thread

4. Comparative tests of steel arch and mixed support systems based on ŁPP10/4/V29/I-type frames

The ŁPP10/4/A/V29/I frames were constructed from S560W steel and had an initial height of H = 4350 mm and width of S = 5430 mm. The tests utilised SDOw29 shackles, which also had reinforced constructions, whereas the shackle screws (class 10.9) in the joints were tightened with a torque of M_d = 350 Nm. Four bolts with trapezoidal Tr22/13 threads were used to reinforce the support frame camber.

Fig. 13 presents the courses of ŁPP10/4/A/V29/I support frame tests in rigid and yielding states, including the value of support work W.

One test was conducted for a rigid frame and two tests for yielding frames. The frame test courses are of a very similar character. The initial frame load capacity is approx. 300÷350 kN during the first stage of loading (up to 100 mm of support height reduction), whereas at the final stage the load capacity increases to a value exceeding 500 kN, though that occurs at a height reduction of ΔH > 750 mm. Similarly as in the case of the ŁP10/V36 support, the rigid and yielding ŁPP10/4/A/V29/I support loading courses, depicted on charts in Fig. 13a and 13b, differ greatly in maximum load capacity and work.

Fig. 14 presents the test courses of ŁPP10/4/A/V29/I support frames reinforced by means of four bolts with trapezoidal Tr22/13 threads, including support work W.

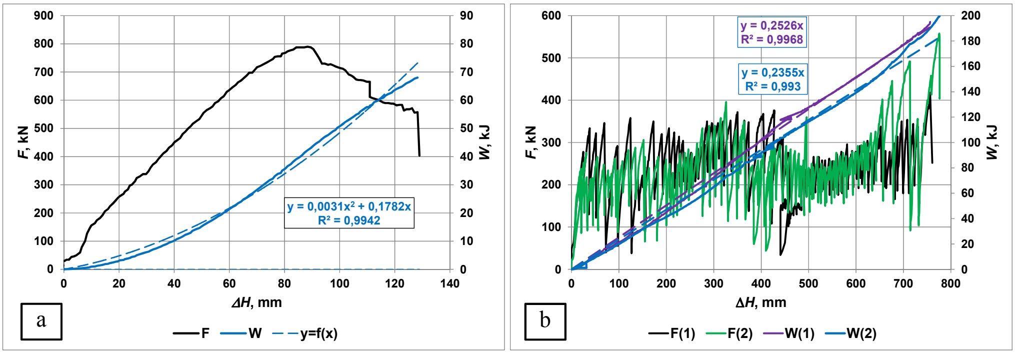


Fig. 13. Courses of ŁPP10/4/A/V29/I frame tests in: a – rigid state; b – yielding state

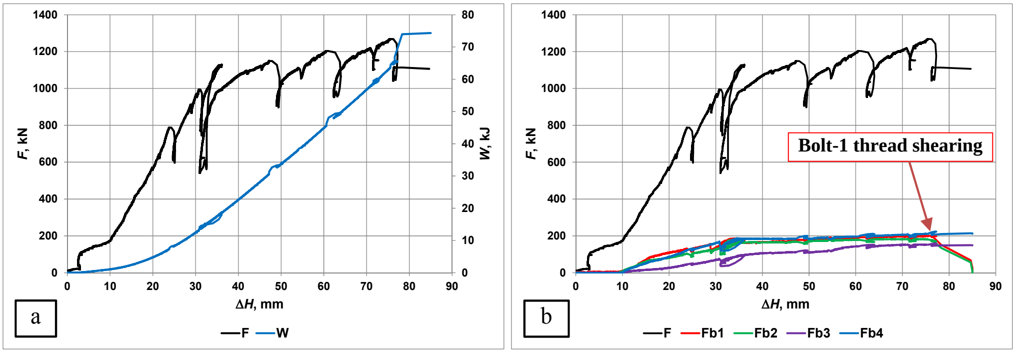


Fig. 14. Courses of: a – loading force F as a function of the height reduction ΔH of ŁPP10/4/A/V29/I support frames in yielding state, reinforced with four bolts (with Tr22/13 threads) coupled to a short joist constructed from a V25 section; b – the force loading the frames and bolts

The shearing of the bolt-1 rod nut thread resulted in the rapid height reduction of the frame, though the bolt did not lose its load capacity entirely, as the nut came to a halt on the subsequent crests of the thread. The bolt rod nut thread shearing commenced at F_{max} = 1268 kN, the frame height reduction was ΔH = 76 mm and the calculated support work was $W \approx$ 74 kJ. The frame height reduction was very rapid, which resulted in the rupture of the draw wire displacement sensor, therefore the subsequent course of support loading is presented on a chart (Fig. 15) as a function of time t.

As presented on the charts in Fig. 15, following its rapid yield the support exhibited significantly lower load capacity, with a maximum range of 300÷450 kN. It can also be observed that the ŁPP10/4/A/V29/I support loading courses depicted in Fig. 14 and 15 exhibit a beneficial property in that the support load capacity remains close to the value of 1200 kN for the major part of the test. This may indicate the good interaction of the yielding support frame, the rock bolts and the short joists constructed from V25 sections.

In order to inspect the operational characteristics of a single bolt with a trapezoidal Tr22/13 thread, it was subjected to a tensile test (comparable to the test of the self-drilling bolt with an

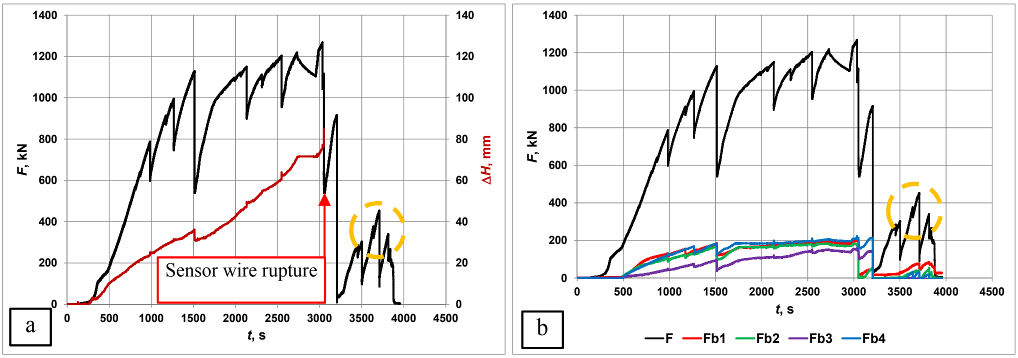


Fig. 15. Courses of: a – loading force F as a function of the height reduction ΔH of ŁPP10/4/A/V29/I support frames in yielding state, reinforced with four bolts (with Tr22/13 threads) coupled to a short joist constructed from a V25 section; b – the force loading the frames and bolts

R25 thread) according to the loading diagram presented in Fig. 4. The tensile test results of three 3 m-long sample bolts as well as a sketch of the thread outline are presented in Fig. 16.

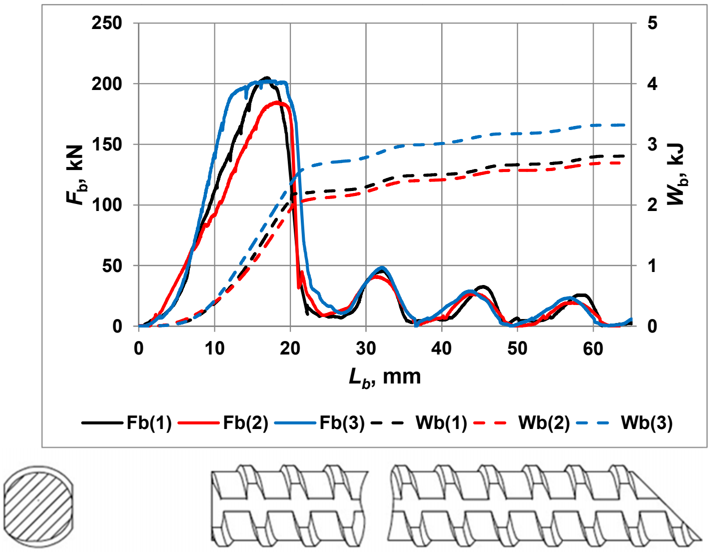


Fig. 16. Loading courses of bolt rods with Tr22/13 threads with force F_b, and the value of work W_b as a function of bolt rod elongation L_b

The tests confirmed that after the shearing of the nut thread with a force of 180÷200 kN (at bolt deformation lower than 20 mm) the bolt continues to be able to transfer the load, but with a value of approx. 40÷50 kN, which decreases progressively together with the shearing of further thread crests.

5. Test result analysis and discussion

Given the many years of experience that the Laboratory of the Central Mining Institute has in conducting steel arch support testing according to Polish standards, it was decided to conduct comparative testing of a steel arch support system with and without bolt reinforcement, with reference to the standard load diagram included in an applicable standard (PN-G-15022:2018-11). It should however be noted that the actual support loading under in situ conditions is not symmetric. This loading depends not only on the geological and mining conditions present in the working, but also on the operational characteristics of the yielding support itself, where the sliding joints never act in unison, and the sequence of the yields in individual joints is usually random.

A compilation of the comparative test results of the non-reinforced ŁP10/V36 steel arch support and the ŁP10/V36 mixed support reinforced with four R25 bolts is presented in Table 1.

TABLE 1

Compilation of comparative test results of the ŁP10/V36 support with and without reinforcement by means of rock bolts

Support type	**Maximum load capacity F_{max}, kN, during the 1st stage of loading: $\Delta H \leq$ 100 mm**	**Support work W, kJ, during the 1st stage of loading: $\Delta H \leq$ 100 mm**	**Maximum load capacity F_{max}, kN, during the 2nd stage of loading: 100 < $\Delta H \leq$ test conclusion**	**Total support work W, kJ, during the 1st and 2nd stages of loading: 100 < $\Delta H \leq$ test conclusion**	**Post-test support condition**
Rigid ŁP10/V36 support	1602	101	1574	154	Camber beam deformation
Yielding ŁP10/V36 support	400	23	1003	288	No support frame arch deformations
Yielding ŁP10/V36 support + R25 bolts (joists: V32)	1226	61	—	—	No support frame arch deformations; Bolt rupture
Yielding ŁP10/V36 support + R25 bolts (joists: V25)	1511	87	—	—	No support frame arch deformations; Bolt rupture

The analysis of the obtained support loading courses and the results compiled in Table 1 demonstrated that the mixed support constructed from ŁP10/V36 frames and R25 bolts with V25 joists and work W = 87 kJ exhibited the greatest load capacity. Despite the fact that the V25 section has much lower strength parameters than the V36 section, it was thanks to its deformation that an equalisation of the loads on the bolts occurred during testing. Consequently, this resulted in more uniform bolt operation. The increase in the work of the mixed support with V25 joists is also significant – it resulted from the increased resultant load capacity of the entire support, while the failure of the first bolt occurred after a reduction of the support height by approx. 60 mm. Test courses above 100 mm of height reduction were not registered, but they were similar to the operation of the ŁP10/V36 frame without bolt reinforcement.

Particular consideration should be given to the fact that the ŁP10/V36 steel arch support frames operate at a relatively low load capacity of approx. 400 kN during the initial stage, while the work value is only 23 kJ (Fig. 9). It is only after the significant height reduction of the frame, practically before the stiffening of the joints, that its load capacity can reach a value of approx. 1000 kN, while the work value reaches 288 kJ. On the other hand, the mixed support attains a high load capacity of approx. 1200÷1500 kN (at the same time its work reaches a high value of 87 kJ) after a minor height reduction, which is very important from the perspective of the correct roof support of a working right after it is driven. Similar relationships were observed during the testing of the ŁPP10/4/V29/I support.

The steel arch support constructed from yielding frames without bolt reinforcement reached a load capacity of 300÷350 kN during the first stage, while its value by the end of the test was 550 kN. At the same time, support work W increased almost linearly and reached approx. 20 kJ after a height reduction of 100 mm and 200 kJ after a reduction of approx. 750 mm.

In the case of the mixed support (ŁPP10/4/V29/I frame reinforced with four bolts with Tr22/13 threads), during the first stage of loading the support attained a load capacity of 800÷1268 kN, whereas after the shearing of the bolt nut thread the maximum support load capacity was within F_{max} = 300÷450 kN, while the support work W increased to a value of approx. 74 kJ.

The comparison of the work W values of the yielding ŁPP10/4/V29/I support frame for the 1st stage of loading during tests no. 1 and 2 is very interesting. The work W value during both the tests was approx. 20 kJ, while the maximum force value was in the range of 276÷346 kN. This may indicate that the maximum frame load capacity F_{max} is not the most favourable support

TABLE 2

Compilation of comparative test results of the ŁPP10/4/V29/I support with and without reinforcement by means of rock bolts

Support type	**Maximum load capacity F_{max}, kN, during the 1st stage of loading: $\Delta H \le 100$ mm**	**Support work W, kJ, during the 1st stage of loading: $\Delta H \le 100$ mm**	**Maximum load capacity F_{max}, kN, during the 2nd stage of loading: $100 < \Delta H \le$ test conclusion**	**Total support work W, kJ, during the 1st and 2nd stages of loading: $100 < \Delta H \le$ test conclusion**	**Post-test support condition**
Rigid ŁPP10/4/V29/I support	790	51	712	68	Buckling of the straight segment of the camber beam
Yielding ŁPP10/4/ V29/I support (test no. 1)	346	21	418	195	No support frame arch deformations
Yielding ŁPP10/4/ V29/I support (test no. 2)	276	20	558	200	No support frame arch deformations
Yielding ŁPP10/4/ V29/I support + bolts with Tr22/13 threads (joists: V25)	1268	74	—	—	No support frame arch deformations; Bolt rod thread shearing

frame evaluation parameter, as it has been acknowledged so far. It could instead be the work W value, which is less susceptible to temporary (rapid) variations in force and is related to the value of the support frame height reduction.

It seems alarming that the work value $W = 20 \div 21$ kJ of the yielding ŁPP10/4/V29/I support frame during the 1st stage of loading was only slightly lower than the work value of the ŁP10/V36 frame, which was $W = 23$ kJ. This could be influenced by the relatively minor difference between the nominal tightening torques M_d of the shackle bolt nuts, which according to documentation were: M_d = 350 Nm for SDOw29 shackles in ŁPP10/4/V29/I frames and M_d = 400 Nm for SDOw32/34/36 shackles in ŁP10/V36 frames. This demonstrates the necessity to increase the tightening torques of the SDOw32/34/36 shackle bolts.

Plans for the future include incorporating the test results into numerical models (Brodny, 2012a, 2012b, 2013; Horyl et al., 2014, 2017; Kang, 2014; Tokarczyk et al., 2010) used in computer simulations, which will make it possible to expand the analyses for a broader range of mixed support variants.

6. Conclusions

The obtained test results in the form of load courses and work values of the steel arch and mixed (arches and rock bolts) support systems demonstrate that the utilisation of mixed support may significantly improve the stability of workings, particularly immediately after they are driven. A mixed support system quickly achieves its maximum load capacity together with a significant increase in its work value. It may thus prevent the stratification of the rocks surrounding the working, and therefore better utilise the self-supporting capacity of the rock mass. As evidenced by the test results, the value of the mixed support work W may be even as much as 3.5 times as great compared to the steel arch support at the beginning of the height reduction process initiated by loading – i.e. until its reduction by a presupposed value of 100 mm.

The short joists constructed from V sections, used to couple the yielding support frame with rock bolts that constitute rigid support, should ensure the optimal interaction of both the support types through the maximum utilisation of their load capacity and deformation. This will also make it possible to greatly increase the work values of the support.

The developed mixed support bench test methodology and the modernised test facility make it possible to determine the actual resultant load capacity and work of the mixed support, which are parameters that are hard to define using computer calculations due to the non-linearity of the material characteristics and the influence of the deformations of the many support elements.

The steel arch support tests will continue for variable loading diagrams, not only for those as described in standards, but also for those resulting from actual directions of load observed in mines.

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