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NOTES

Pressure Sensitive Mats as Safety Devices in Danger Zones

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Developing prototypes of pressure sensitive mats and testing their practical application were the aims of this study. Two contact plate mats were designed and constructed: rubber-rubber (R) and metal-metal (M). A recipe for rubber mixes and the production technology were prepared. Two laboratory test stands for measuring the actuating force, response time, static pressure resistance, and the durability of the mats were constructed. Computer software was written to control the operation of those test stands. Methods of testing pressure sensitive mats were based on PrDIN 31 006 (Deutsches Institut für Normung [DIN], 1990) and EN 1760–1 (Comité Européen de Normalisation [CEN], 1997). Both prototypes of contact plate mats were tested under laboratory and industrial conditions.

The test results proved that the design was correct, the setup requirements were fulfilled, and the mats were efficient and reliable in the industrial environment.

pressure sensitive mat   safety sensor   danger zone   safety device

1. OBJECTIVES

Effective protection against hazards, especially at mechanized workstations, requires safeguards and safety devices, which can be integrated into systems. Pressure sensitive mats are among the safety devices that are

The study described in this paper was part of a State Committee for Scientific Research of Poland research project carried out by Stanisław Dąbrowski, Zygfryd Brański, Ryszard Buczek, Bogdan Felczak, and others.

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effective in protecting against severe injuries and fatal accidents in danger zones. They are increasingly common at various workstations in the industry as well as in everyday life.

Pressure sensitive mats can indicate the value of the pressure force. However, they do not identify the source of the pressure force: Mats can be activated by a person, a vehicle, or an object (e.g., a piece of processed material).

Depending on the hazard at a workstation, there are a few scenarios that can take place after a mat has been activated by a pressure force. The signal from the mat can cut off the power supply to machines or equipment, stop the program that controls the production process, reduce the speed or range of movement of a machine part, or switch on light or sound signalling circuits. Eliminating the pressure force (e.g., by a person stepping off the mat) and switching on the control units can restore the former state of the machine or equipment.

A pressure sensitive mat comprises a sensor (or sensors), which responds to the application of pressure and a control unit with an output signal switching device (EN 1760–1; Comité Européen de Normalisation [CEN], 1997). Pressure sensitive mats are produced by many companies around the world (e.g., AEMB, BIRCHER, COMETA, EREIS, GUARDSCAN, HERGA, LANSON, MATEX, MAYSER, SWITCH, TAPE). Those firms also conduct research aimed at developing new designs and improving the existing ones.

Nowadays, pressure sensitive mat sensors are based on several principles:

1. *Contact plate mats*

   The mat sensor has two conductive plates separated by an elastic insulating layer. Pressing the mat causes a shorting of the conductive plates and sending information to the control unit.

2. *Pneumatic mats*

   A. Active mats. At regular intervals of, for example, 2 s, a pump connected with the mat sensor creates partial vacuum, which is sent to the appropriate switches. Pressure exerted on the mat results in a change of partial vacuum, an impulse is sent to the control unit (Kneppert & Vautrin, 1984, as cited in Buczek, 1991).

   B. Passive mats. There is a closed pressurized circuit built inside the structure. Loading a mat sensor generates overpressure in the circuit, which is detected. Information is sent to the control unit.

3. *Variable resistance mats*

A. Contact plate mats. They are based on the on-off control principle. These mat sensors are constructed with two conductive layers separated by evenly distributed insulating cylinders. A constant resistor connecting both conductive layers is monitored by the control unit. Loading the sensor causes a shorting of the conductive layers, which changes the resistance of the circuit. This is detected by the control unit.

B. Analogue mats. They are made of two flexible polyurethane layers. One of them is a conductor, the other one has conductive properties under the influence of an external force only. Particles of the conductive material located in polyurethane shorted by the external force change the resistance of the measuring circuit. This is detected by the electronic controller connected with the mat sensor.

4. *Fibre-optic mats*

Those mats have a sensor, a circle of fibre optic built in under the active surface. The fibre optic is wrapped in an additional plastic spiral (Herga Electric, n.d.). The light beam is processed as it passes along the fibre-optic sensor. The intensity of the light passing along the fibre is reduced by microbending. Light intensity is measured in the output of the sensor. Loading the sensor causes bending the fibre at certain points along its length. Some light is guided out of the core fibre optic, where it is dispersed. A decrease of, for example, light intensity in the sensor output is detected by the controller.

5. *Other mats*

Different methods of detection can be used to build pressure sensitive mats, for example, changes of the intensity of the electric noise in a layer of steel felt (Pruski, 1986) or piezoelectric properties of various materials.

There are both advantages and disadvantages of pressure sensitive mats.

Advantages:

- fast action in the case of pressure caused by an external force or detection of a defect,
- effective protection against hazards,
- good visibility at the workstation,
- possibility of covering a surface of any shape or size.

Disadvantages:

- possible mistakes as—when the loading area increases—the unit pressure can be lower than mat sensitivity threshold per unit area,
- progressive change of work parameters as a result of the ageing of mat materials or aggressive environment. This can be reduced by using materials resistant to agents such as water, oils, solvents, and acids.
- insensitive zones of mats that can be limited or excluded from the working surface of the mat sensor.

Because of their advantages, pressure sensitive mats provide safety without decreasing the efficiency or increasing the difficulty of work. Therefore, workers accept them. The disadvantages of mats are less significant and they can be considerably reduced. Hence, mats can be used wherever danger zones occur, for example,

- in belt system production,
- at robot-assisted workstations,
- in systems, in which it should be impossible to switch on the machinery during loading, unloading, and maintenance,
- at entrances to storage areas with dangerous substances,
- at entrances to high intensity electromagnetic field zones,
- in security systems, as sensors.

Examples of the application of pressure sensitive mats at different workstations can be found in Buczek (1991).

No scientific research related to pressure sensitive mats had been conducted in Poland. That is why, research and implementation work on the use of pressure sensitive mats as safety devices in danger zones was taken up as part of a research project supported by the State Committee for Scientific Research of Poland.

The objectives of the project were

1. to design and construct prototypes of pressure sensitive mats,
2. to design and construct test stands for measuring response time, the actuating force, static pressure resistance, and the durability of mats,
3. to design computer software for controlling the operation of test stands and registering and displaying test results,
4. to test the prototypes of mats, and to draw conclusions.

2. TEST STANDS

Two laboratory test stands (called in this paper A and B) were designed and constructed according to PrDIN 31 006 (Deutsches Institut für Normung [DIN], 1990). They consist of a mechanical structure, control systems, and computer software.

2.1. Laboratory Test Stand A

Laboratory test stand A for measuring the actuating force, response time, and static pressure resistance is shown in Figure 1a. Parts of the test stand are shown in Figures 1b and 1c.

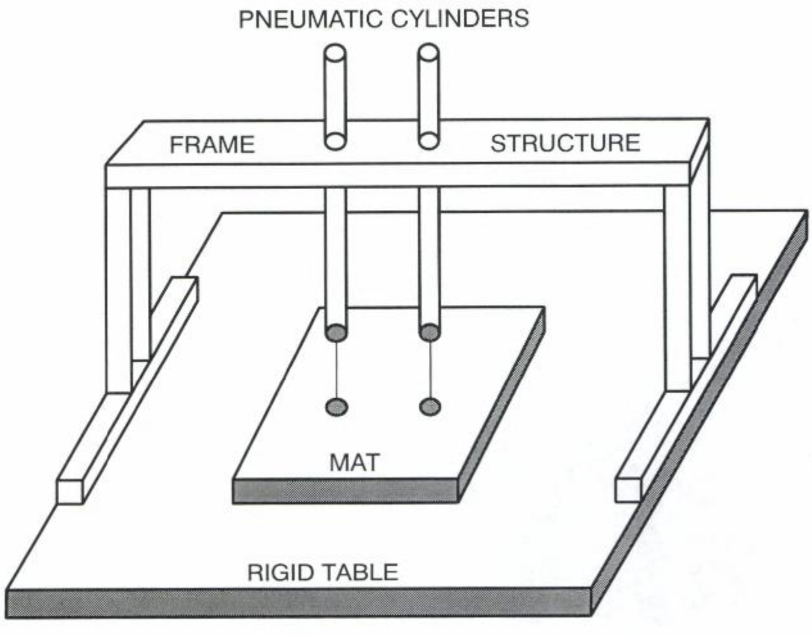


Figure 1a. Test stand A.

Tested mats were put on a rigid base (a table). Pressure on the mats was exerted by a Festo pneumatic cylinder equipped with test pieces at the pistons. There were three test pieces, 11, 80, and 200 mm in diameter. The cylinder was put in motion by a FPC-101B controller that cooperated with a computer. The actuating force, piston stroke, and the test piece's speed of travel were regulated. The force was measured by a Hottinger measuring system. It consisted of a measuring bridge type

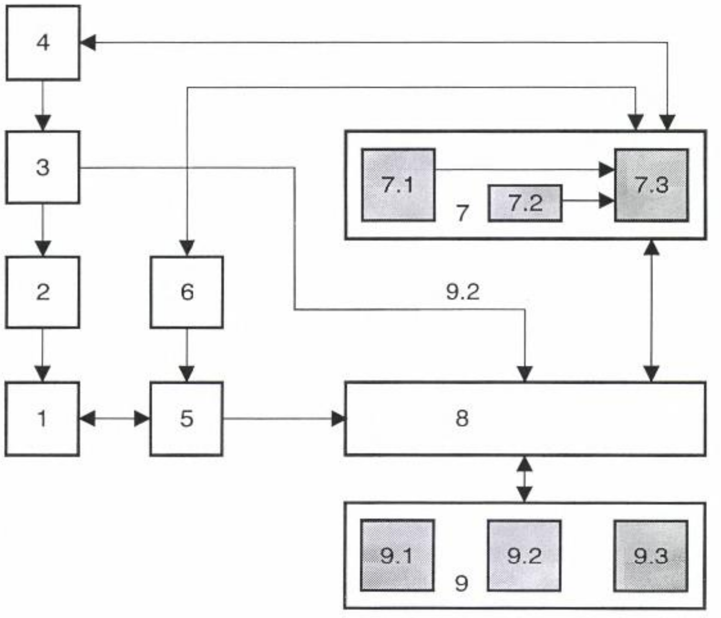


Figure 1b. A block diagram of test stand A. *Notes.* 1—mat sensor, 2—test piece, 3—force measurement unit, 4—pneumatic cylinder, 5—mat control unit, 6—pneumatic cylinder, 7—controller of the test stand, 7.1—power supply, 7.2—emergency stop, 7.3—FPC-101P controller with a main control program, 8—interface unit (coupler), 9—IBM-PC computer with an A/C control and measurement unit, 9.1—program manager, 9.2—test result logging program, 9.3—data presentation and processing program.

Figure 1c. Test stand A for measuring the actuating force, response time, and static pressure resistance.

KWS 3073 and a 0.2 class force transducer type U2 with the range of 200 kg.

Software to control the test stand was created, too. It consisted of

- a program to control the measurement of the mat parameters (actuating force, response time, and static pressure resistance),
- a main control program for the FPC-101B Festo controller,
- a program for logging test results and for controlling the measuring unit,
- a data processing program.

2.2. Laboratory Test Stand B

Laboratory test stand B designed to assess the durability of mats is shown in Figure 2a. The test stand consisted of sets shown in Figures 2b and 2c.

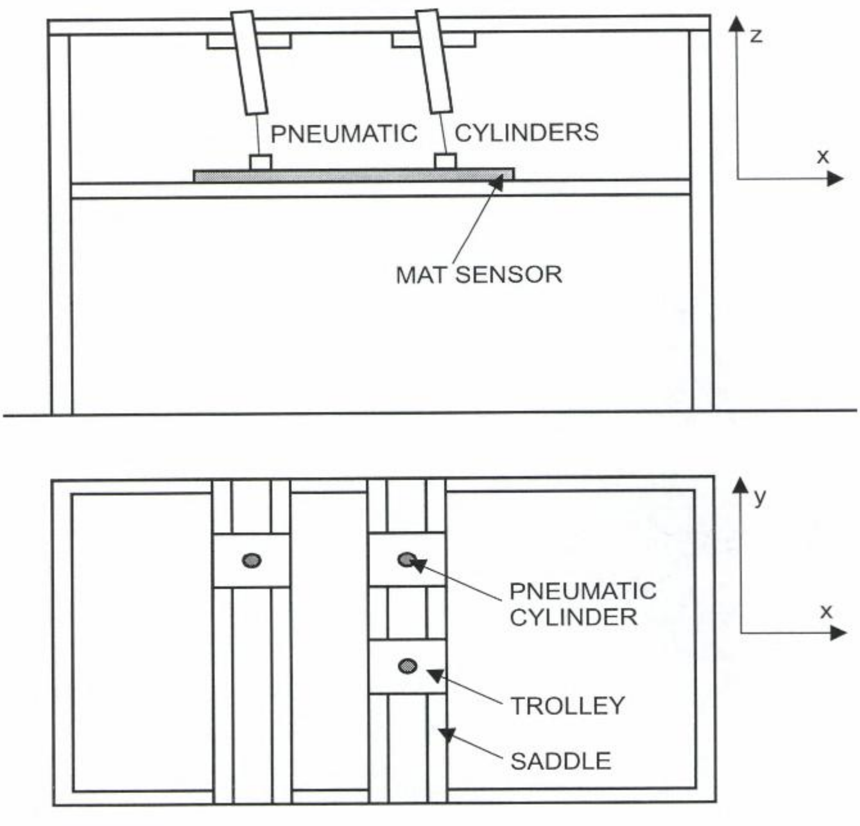


Figure 2a. Test stand B.

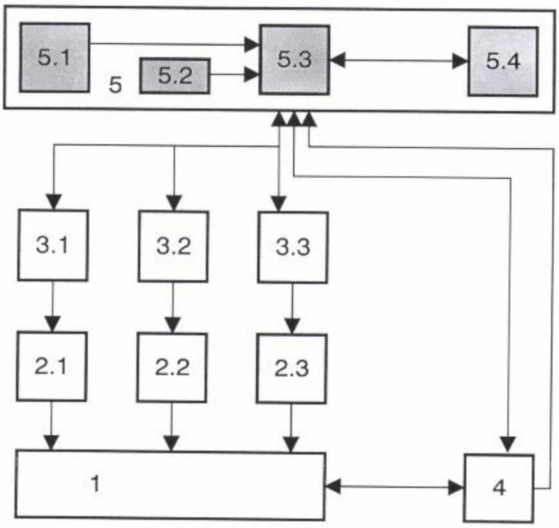


Figure 2b. A block diagram of test stand B. *Notes.* 1—mat sensor; 2.1, 2.2, 2.3—test pieces; 3.1, 3.2, 3.3—pneumatic cylinders; 4—mat control unit; 5—controller; 5.1—power supply; 5.2—emergency stop; 5.3—FPC-101P controller with a main control program; 5.4—BEA-4 indicator panel.

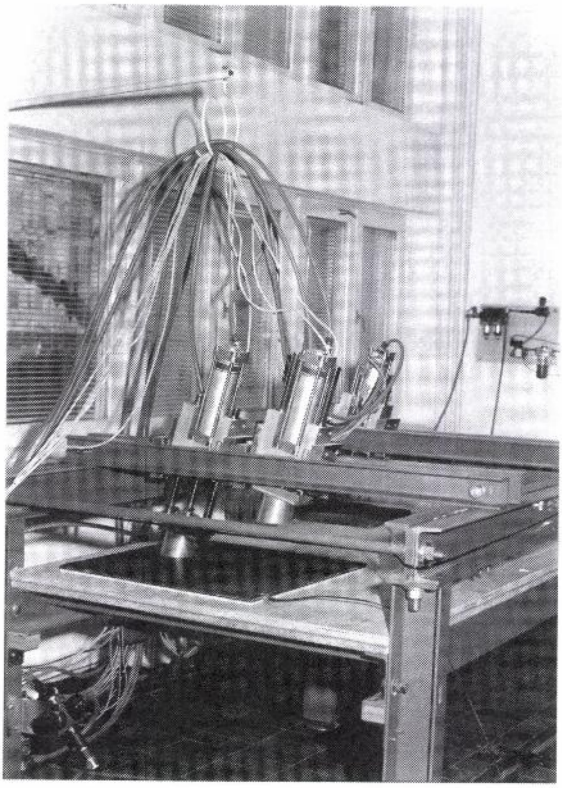


Figure 2c. Test stand B for assessing the durability of pressure sensitive mats.

Tested mats were put on a rigid base (a table). Pressure on the mats was exerted by three Festo pneumatic cylinders fixed over the table at 14°. The pistons were equipped with test pieces 80 mm in diameter. Each of them was cut off at the same angle of 14°. Because of the way the cylinders were fixed, it was possible to exert pressure anywhere on the mat. The force, piston stroke, and the test pieces' speed of travel were set for the test.

The operation of the test stand was controlled by a main control program. A controller logged the data about the operating conditions of the sensors that were installed at the test stand. Moreover, the motion of the cylinders was controlled according to the selected procedure. One, two, or three cylinders could work at the same time. The mat controller was tested at the same time as the durability of the mat sensor.

3. PROTOTYPES OF CONTACT PLATE MATS

Preliminary tests on three models of pressure sensitive mats were conducted. The models tested were contact plate mats, fibre-optic mats, and resistant mats operating on the analogue principle. The best results were obtained for the models of contact plate mats, on which the

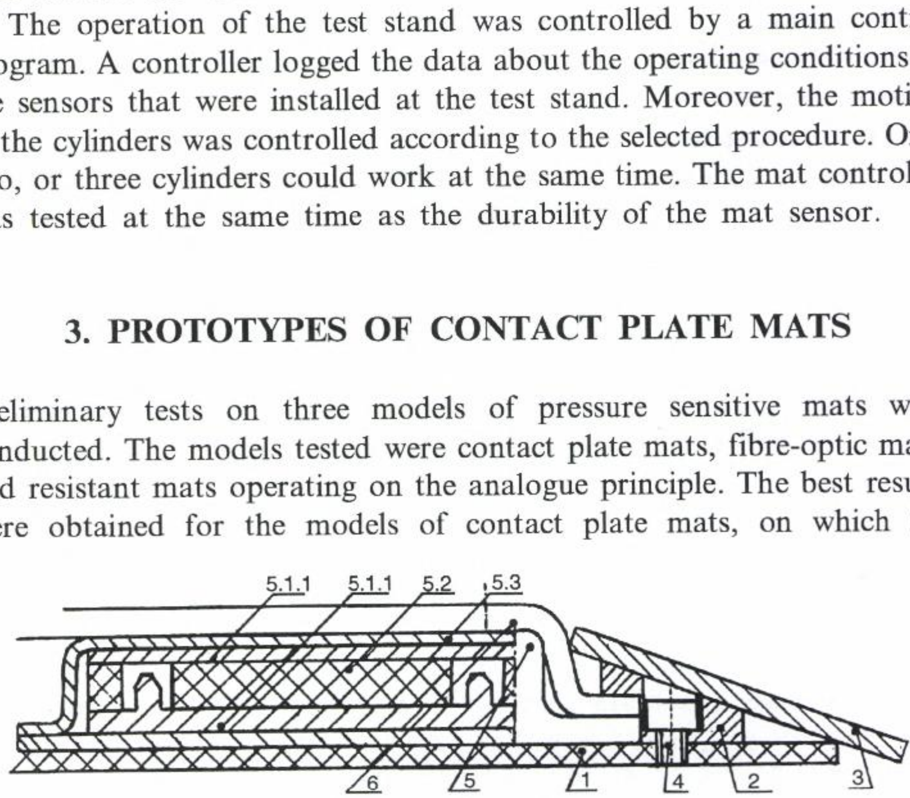


Figure 3. Cross-sections of contact plate mat sensors. *Notes.* 1—metal base plate, 2—support, 3—metal clip slats, 4—screw, 5—sensor elements, 5.1.1—conductive rubber (for R type mat sensors), 5.1.2—metal plate (for M type mat sensors), 5.2—elastic insulating layer, 5.3—rubber envelope, 6—flexible, oil resistant, antislip carpet.

prototypes were then based. The design, recipe for the rubber mixes, and the technology of production were developed. A contact plate mat is shown in Figure 3. It was made of two contact plates separated by an elastic insulating layer. The contact plates were made of conductive rubber for the R type or metal for the M type and closed in a rubber envelope. The whole construction was placed on the metal plate and covered by a flexible, oil resistant, antislip carpet with edges closed by metal clip slats.

The encased mat was joined by a coaxial cable with an electronic control unit consisting of a measuring unit, a logical unit, an output signal switching device, and a power supply. The connection between the contact plates of the mat and the electronic control unit is shown in Figure 4.

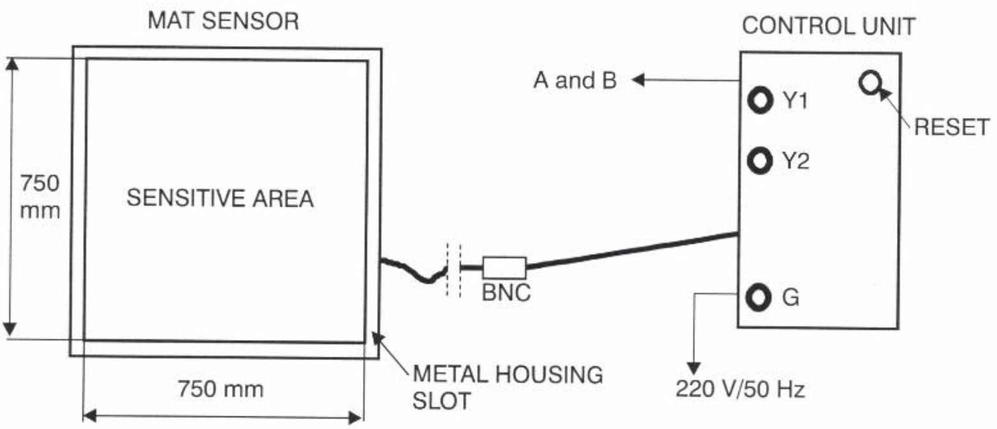


Figure 4. Connection between a mat sensor and an electronic control unit. *Notes.* BNC—joint between contact plate and control unit by coaxial cable; G—mains indicator (green light); RESET—stand-by switch button; Y1, Y2—light-emitting diodes (yellow light—when mat is loaded); A, B—relay contacts (to be connected with any signalling unit or machine control unit).

4. TESTING PROTOTYPES OF CONTACT PLATE MATS

The prototypes described in section 3 were put to laboratory and functional tests.

4.1. Tests at Laboratory Test Stands A and B

Two samples of each prototype of contact plate mats were tested. Additionally, one sample of each prototype of combined mat sensors was tested. Those tests were conducted for both types of mats, that is, rubber-rubber (RR) and metal-metal (MM).

The following parameters of the mats were measured: actuating force *F* (N), response time *t* (s), and static pressure resistance of 750 N—on test stand A, and durability *D* (the number of pressures)—on test stand B.

The tests were performed in accordance with the instructions and measuring cards prepared on the basis of PrDIN 31 006 (DIN, 1990). The location of test points for the measurement of actuating force *F* and response time *t* are shown in Figure 5. Because this document does not determine permissible response time, the test result for this parameter was compared with the draft of the European standard EN 1760–1 on pressure sensitive mats and floors (CEN, 1997). According to this draft standard, the permissible value of the response time should be lower than 200 ms. Test results are shown in Table 1 and in Figure 6.

TABLE 1. Results of the Measurements of the Actuating Force and Response Time

Tested Parameter	Test Piece	EN 1760-1 Requirements	Mat Sensor Type and Number: R 1	R 2	M 5	M 6	RR	MM
Force *F* (N)*	A/11	300	49.6	68.9	89.6	89.5		
	B/80	300	94.8	102.3	90.9	96.8	106	75
	D/200	600	248.3	228.9	113.7	127.6		
Time *t* (s)*	C/80	0.2	0.085	0.1	0.042	0.039	0.104	0.066
Static pressure: 750 N			no change	no change	no change	no change		
Durability *D* (10^5 operations)			no change		no change			

Notes. R1, R2, M5, M6—single mat sensors; RR, MM—mat sensors in dual configuration. *—Mean value from 5 measurements in each test point shown in Figure 5.

The results of measuring the actuating force showed that prototypes of both types of mats (R and M) met the requirements of PrDIN 31 006 (DIN, 1990). They were comparable with mats available in Europe.

However, there were differences between R and M types of mats in response time, which should affect their applicability. Thus, the prototypes of the R (rubber-rubber) type mats were more sensitive to a small area of pressure than the prototypes of the M (metal-metal) type.

The R1, R2, M5, and M6 prototypes of mats were tested for static pressure resistance of 750 N. The plastic deformation of 1 mm, which

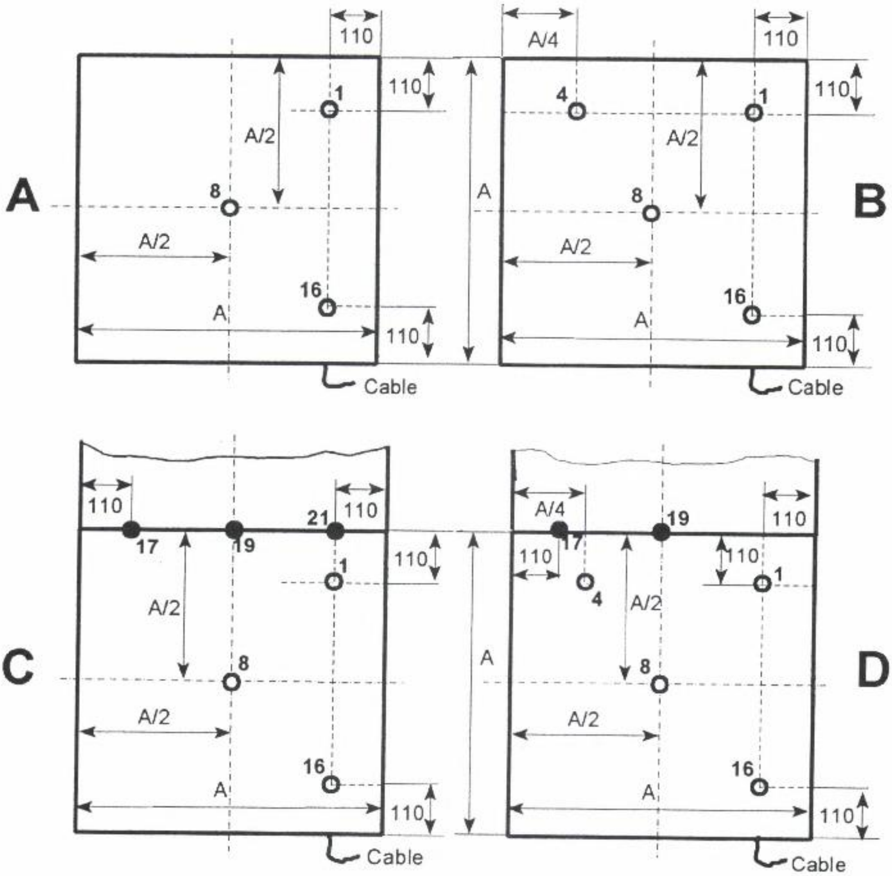


Figure 5. Measurement points on mat sensors for the assessment of actuating force *F*, response time *t*, and static pressure resistance on test stand A. *Notes.* A—a single mat sensor, measurement of actuating force *F* in points 1, 8, and 16; B—a single mat sensor, measurement of response time *t* in points 1, 4, 8, and 16; C—a combined mat sensor, measurement of actuating force F in points 1, 8, 16, 17, 19, and 21; D—a combined mat sensor, measurement of response time t in points 1, 8, 16 17, and 19.

occurred after 1 hr, falls within the requirements of EN 1760-1 (CEN, 1997; This standard permits plastic deformation of 2 mm.) After the tests, the mats operated properly without any changes in sensitivity.

The durability of the R1 and M5 prototypes was tested, too. An A/80 test piece cut off at the angle of 14° was used during the test. The mats was pressed at the same angle of 14° with a force of 750 N. The test were made in two direction, x and y, perpendicular to each other and to the edge of the mats. The test points are marked in Figure 7.

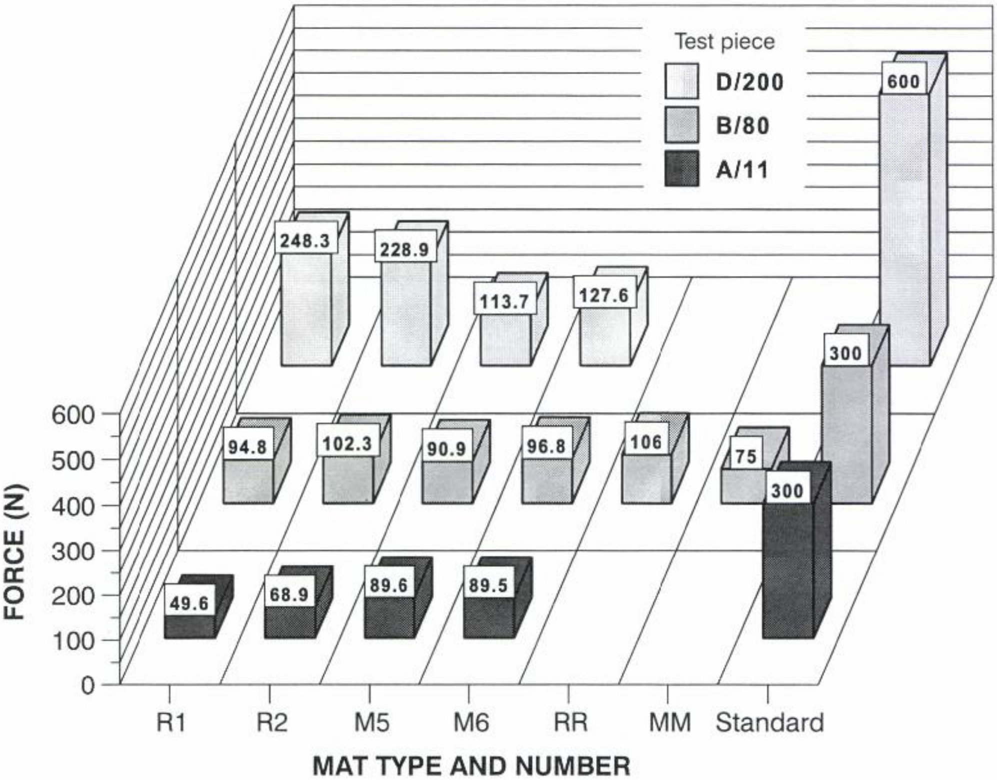


Figure 6a. Actuating force of rubber-rubber and metal-metal mat sensors. *Notes.* R1, R2—rubber-rubber mat sensors; M5, M6—metal-metal mat sensors; RR—rubber-rubber mat sensors in dual configuration; MM—metal-metal mat sensors in dual configuration.

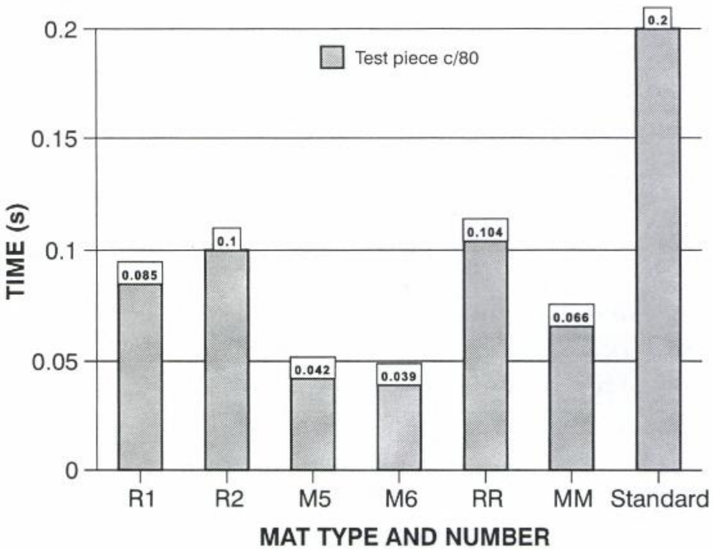


Figure 6b. Response time of R and M type mat sensors. *Notes.* RR—R type mat sensors in dual configuration, MM—M type mat sensors in dual configuration.

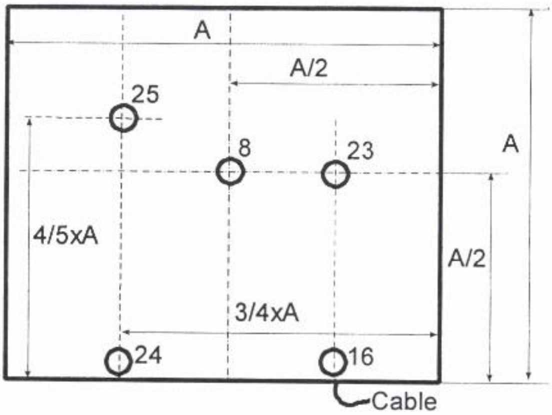


Figure 7. Measurement points on a mat sensor for durability test on test stand B. *Notes.* Points 24 and 25 optionally selected but different from points 8, 16, and 23. A—dimension; 8, 16, 23, 24, 25—points on the mat.

Both tested prototypes retained their efficiency after 100,000 operations in each location, in both directions (x and y), which conforms to both standards, EN 1760-1 (CEN, 1997) and PrDIN 31 006 (DIN, 1990).

4.2. Functional tests in the industry

After positive test results were obtained at test stands A and B at the Central Institute for Labour Protection in Warsaw, Poland, an instruction manual for the R and M types of contact plate mats was prepared. The mats were also tested functionally in the industry.

4.2.1. Ursus Tractors Works (Zakłady Przemysłu Ciągnikowego Ursus)

Both types of mats (R and M) were used at an AMADA Japanese automatic steel sheet cutting machine (Figure 8) at the Ursus (Poland) tractors works. This machine is used for cutting out different shapes of steel sheets according to specified programs. The steel sheets to be cut are stacked at a coordinate table, which—due to its fast moves—is dangerous.

The mats were installed in front of danger zones and connected via an electronic control unit with the machine control systems and light and sound signalling. Every time a person stepped onto the mat, the machine was switched off and the light and sound signals were switched on. The mats worked without any problems and remained efficient. The RESET button was used to switch back the mat to its stand-by status.

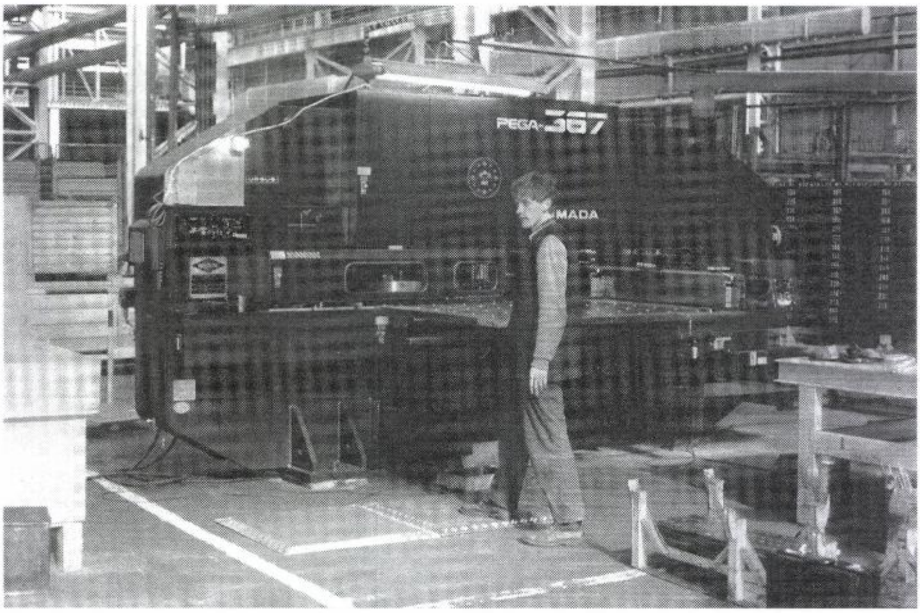


Figure 8. A workstation at an AMADA automatic steel sheet cutting machine.

4.2.2. High Voltage Apparatus and Switchgear Group of Factories (Zakłady Wytwórcze Aparatury Wysokiego Napięcia ZWAR)

Both types of mats were also installed at four workstations at ZWAR (Poland), a producer of a high voltage apparatus for the power industry.

Entering the workstations was possible across a mat only. Every time a person stepped onto the mat, the light and sound signals were switched on. The RESET button was used to switch back the mat to its stand-by status. High intensity electromagnetic fields, mechanical vibration, and industrial disturbances did not have any negative influence on the operation of the mats.

4.2.2.1. Test stand for electromechanical tests of a WVK type high voltage column vacuum switch (Figure 9)

During the operation of a high voltage switch, mechanical vibrations take place, so electric shock and mechanical injuries are possible. Mats were located on the same metal platform as the tested switch. Thus, they were subject to shocks and vibration caused by the operation of the switch.

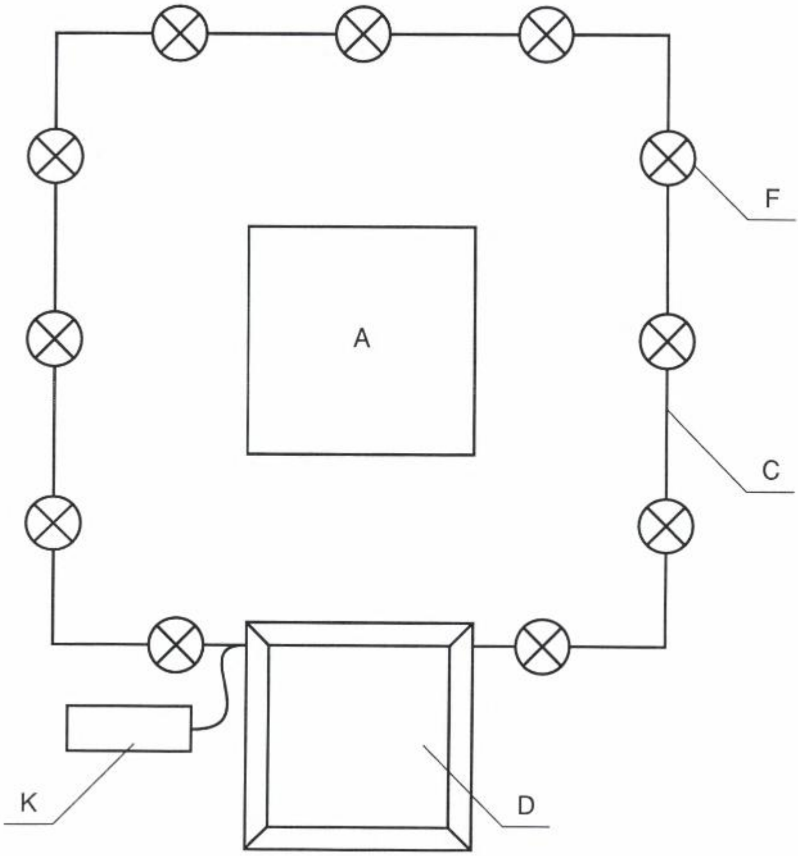


Figure 9. A test stand for electromechanical tests. *Notes.* A—WVK type high voltage column vacuum switch, C—fenced protected area (danger zone), D—mat sensor, F—light signalling, K—control unit.

4.2.2.2. Test stand for short-circuit tests of a ROK 6 V type mine switchgear (Figure 10)

During the work of this test stand, high intensity electromagnetic fields occur due to the current flowing across the main circuit of the switchgear. The 20 kA current created an electric shock hazard.

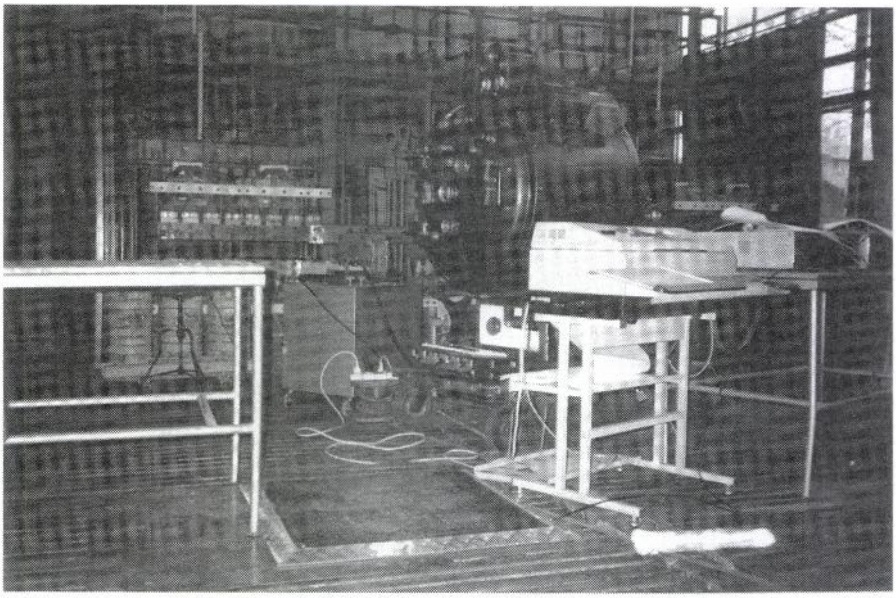


Figure 10. A test stand for short-circuit tests.

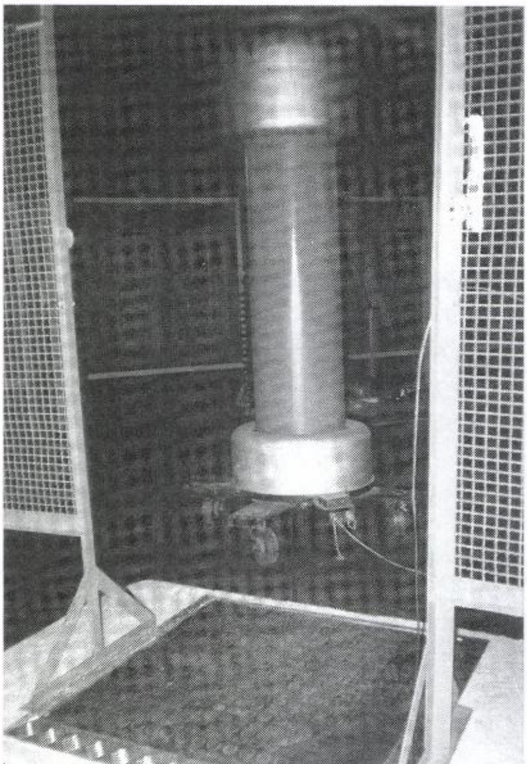
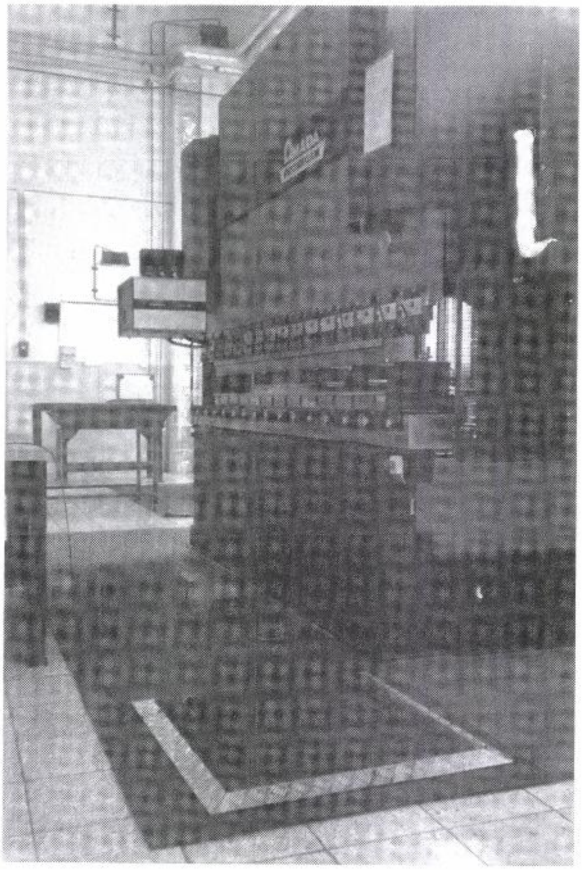
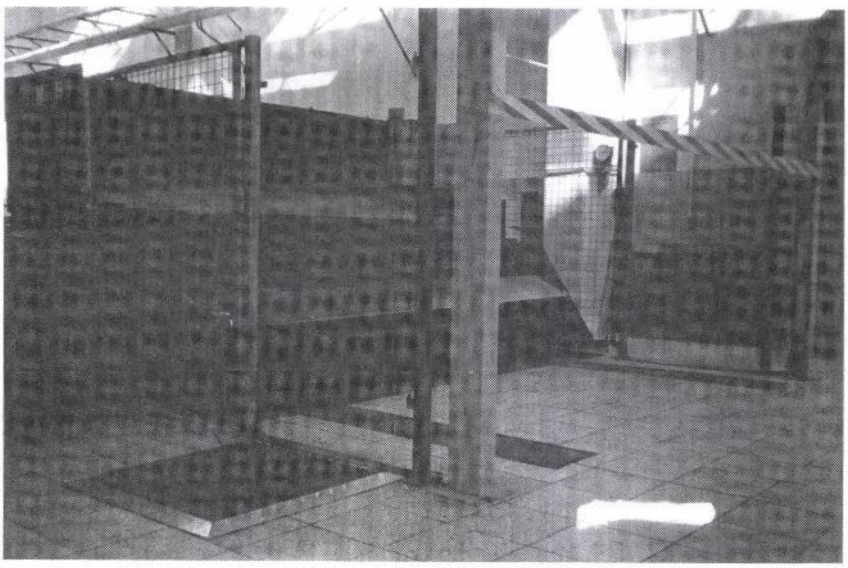


Figure 11. A high voltage test stand.





Figures 12a and 12b. A power press workstation.

4.2.2.3. Test stand for electric strength tests of a high voltage insulator up to 200 kV (Figure 11)

Mats were installed 2 m from a transformer. During work at the high voltage stand, the insulator was supplied by a test transformer type 1100. The rise time of peak voltage up to 460 kV/50 Hz was 5 ms. This created high intensity electromagnetic fields and an electric shock hazard.

4.2.2.4. Power press workstation on the shop floor (Figures 12a and 12b)

When operating a power press, there is a high risk of mechanical injuries from a moving part of the machine.

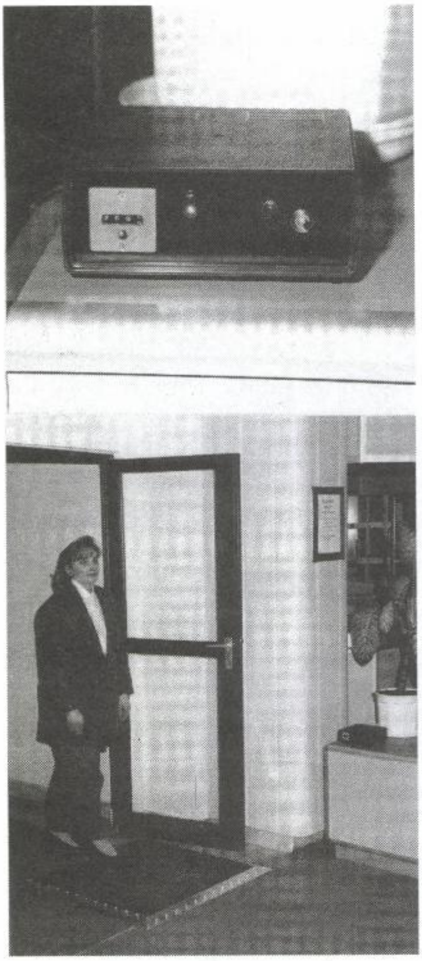


Figure 13. A functional test of a pressure sensitive mat.

The mats at this workplace were installed in front of the danger zone and connected via an electronic control unit with the machine control systems and light and sound signalling.

4.2.3. Central Institute for Labour Protection

Both types of mats were installed at the entrance to the Central Institute for Labour Protection. The mats were equipped with a light and sound signalling unit and a counter (Figure 13). When a mat was stepped on, the pressure was recorded and the light and sound were switched on. The mats worked without any problems and remained efficient.

5. CONCLUSIONS

1. The test results of the prototypes of the R (rubber-rubber) type and the M (metal-metal) type contact plate mats proved the following:
   - The designs of the mats were correct.
   - The setup requirements were fulfilled.
   - The mats worked efficiently and reliably.
   - The mats worked properly in the industrial environment even where electromagnetic fields were present.
2. Because of their high sensitivity, the R (rubber-rubber) type mats were better than the M (metal-metal) type mats at those workstations where pressure was applied to a small area.
3. Test results also indicated that the following recommendations should be considered when producing and using contact plate mats:
   - Because of their high sensitivity, R (rubber-rubber) type mats should be used at those workstations where pressure is applied to a small area.
   - When mats are used in front of workstations with high intensity and frequency electromagnetic fields, appropriate distance between the mats and the power source should be preserved. A design modification of the whole unit (mat sensor, controller, cables, connectors) is also required. The disturbances caused by high intensity and frequency electric fields can be eliminated by enclosures.

- The design of a mat enclosure should make linking to increase the pressure sensitive area in front of danger zones possible.
- A metal housing slat with appropriate strength and accuracy should allow placing cables and connections inside and linking mat sensors to increase the pressure sensitive area.
- Both R and M type mat sensors should be equipped with envelopes that make contact plate movement in relation to the enclosure and the other contact plates impossible.
- The design of the enclosure should provide various ways of fastening the mat to the foundation (e.g., directly to the floor or to floor recesses) to eliminate the hazard of stumbling against it.
- Manufacturing of mat sensors with higher static pressure resistance should be considered, so the sensors work when a forklift truck drives onto them.
- The output parameter of the electronic control unit should be listed in performance data.
- Other operational options, for example, automatic resetting of the system, should be provided according to the buyers' requirements.

Research related to fibre-optic and resistant mats (based on the materials with variable conductive properties) should be continued.

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