Corrosion of connectors used in equipment protecting against falls from a height

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Connectors are commonly found in personal equipment protecting against falls from a height. They are typically used outdoors and exposed to atmospheric factors, which can result in corrosion. This article presents the results of a study involving exposure of connectors to experimental corrosive media – neutral salt spray (NSS), acid salt spray (ASS), and seawater mist (for elements made of carbon steel and non-ferrous metals) – and to experimental conditions simulating the processes of pitting, stress, and intercrystalline corrosion (for equipment made of stainless steel). The results indicate that the main effects of corrosion on connectors include impaired operation and reduced strength of their mobile elements. The article presents methods of testing connector operation developed for this purpose. Corrosive damage to connectors has been presented in relation to potential hazards for their users.

Keywords: personal protective equipment; connectors; corrosion; falls from a height

1. Introduction

Data concerning work at a height, published annually in many European countries,[1,2] indicate that it is one of the most hazardous occupations. In such sectors as civil engineering, power engineering, and telecommunications, the use of personal fall-arresting equipment is still the most popular method of protection available for workers; in fact, sometimes it is the only method. Connectors, defined by Standard No. EN 362:2004 [3] as mobile devices which can be opened and are used for connecting components, are commonly applied in such protective systems. They enable the user to assemble the elements of the protective system and to connect it, directly or indirectly, to an anchor component. They are used as connecting elements in systems preventing falls from a height to assist in work positioning and rope access, in restraint systems, and in rescue systems. They are most frequently employed to connect a full-body harness with a connecting energy-absorbing component, and that component with an anchor element.

Connectors, as well as other components of personal equipment protecting against falls from a height, are often used outdoors; therefore, they are exposed to atmospheric factors.[4] They can be installed on building exteriors as permanent protective elements. Such sites, e.g., in coastal areas, the chemical industry, or power plants, are often associated with exposure to particularly aggressive microclimates. One of the most serious consequences of such exposure is corrosion of metal elements.[5,6] Information received from both the users and the manufacturers of personal protective equipment indicates that corrosion processes may have a direct effect on worker safety. For this reason, during 2004–2008 the Central Institute for Labour Protection – National Research Institute (CIOP-PIB) carried out studies addressing this problem, whose results were published in reports.[7–9] The present article is based on the data collected during those studies; it discusses the results of corrosion of metal elements in connectors used as components of personal equipment protecting against falls from a height.

2. Connectors: design and principles of operation

Taking into consideration differences in structure and application, Standard No. EN 362:2004 [3] classifies connectors, elements of personal equipment protecting against falls from a height, into five basic types. Table 1 presents examples of selected constructions of connectors.

As a result of an analysis of selected connectors, the following essential elements can be distinguished:

- body, fitted with a self-closing gate;
- self-closing gate equipped with a self-locking gate system or designed to make uncontrolled opening impossible;
- spring for automatic closing and locking of the gate; and
- rivets and axles.

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Table 1. Classification of connectors [3].

| Number | Class | Name                     | Application                                                                 | Additional information          |
|--------|-------|--------------------------|----------------------------------------------------------------------------|----------------------------------|
| 1      | B     | Basic connector          | Self-closing connector used as a component                                 | Figure 1                        |
| 2      | M     | Multi-use connector      | Basic or screw-link connector used as a component, withstands load in the major and minor axis | Figure 2                        |
| 3      | T     | Termination connector    | Self-closing connector used as a termination of connecting and energy absorbing components | Figure 3                        |
| 4      | A     | Anchor connector         | Self-closing connector linked directly to elements of work sites           | Figure 4                        |
| 5      | Q     | Screw-link connector     | Connector which is closed by a screw-motion gate, used only for long-term or permanent connections | Figure 5                        |

(a)  
(b)

Figure 1. Class B connector: (a) class B with self-locking gate, made from carbon steel with zinc layer; (b) class B with a manual-locking gate, made from carbon steel with zinc layer.

Figure 2. Class M connector.

Figure 3. Class T connector: (a) class T with manual locking (a manual-locking gate, made from aluminum alloy); (b) class T with automatic locking (a self-locking gate, made carbon steel with chromium layer).

The structure of the connector and the joint operation of its constituent parts are supposed to ensure that individual components of a protective system are connected easily, quickly, and safely. Connector operation includes the following:

- Opening and closing the gate – this occurs when the components of equipment protecting against falls from a height are being assembled and disassembled, or when accessory components are being connected to it; the return movement of the self-closing gate (closing) is automatic.
- Switching the self-locking gate system on and off – this occurs during safety locking and unlocking of the connector gate and can be done manually or automatically.
From an analysis of catalogs of leading manufacturers of connectors used in the European Union, most of their elements are made of steel or non-ferrous metal alloys. Table 2 presents examples of materials used in typical connector structures.

3. Connectors: testing

Tests of used equipment protecting against falls from a height (primarily protective systems mounted permanently on building exteriors) carried out at CIOP-PIB [7–9] demonstrated numerous defects (e.g., in steel ropes and connectors) that resulted from corrosion. This process caused damage both to the mechanisms (springs, self-locking gates) and to the main construction element (i.e., body) of connectors. An analysis of the test results has shown that the two most dangerous consequences of corrosion processes are as follows:

- impairment of the operation of, e.g., the mobile elements or automatic gate lock; and
- reduced mechanical strength of connector elements (e.g., the body or self-closing gate).

Laboratory tests of connectors exposed to corrosive environments therefore focused on the observation of the following:

- corrosion of the base metal in connector elements;
- corrosion of the protective layer, e.g., zinc coating on connector elements;
- operation of the self-closing gate [3];
- operation of the self-locking gate [3]; and
- decrease in the mechanical strength of the connectors.

3.1. Test specimens

Tests of used equipment revealed a number of problems associated with connector corrosion. However, the variety of equipment types and corrosive environments in which they were used made it impossible to comprehensively assess corrosion-related problems in equipment protecting against falls from a height. Therefore, we decided to conduct laboratory tests on new connectors subjected to simulated corrosive environments.

The popularity of connector types and materials was the basic criterion for the selection of test specimens. The selected connector types included class T connectors with manual-locking gates (made of aluminum alloy) and self-locking gates (made of carbon steel), class B connectors with manual-locking and self-locking gate versions, made of carbon steel, and class Q connectors made of stainless steel; 10 pieces of each type. In total, five connector types representing different construction solutions and made of different materials were selected for tests (see Table 1). The numerical results of tests in Section 4 also include $M$ and $SD$ values.

3.2. Methods

To determine the safety parameters of connectors, the following features were selected on the basis of previous results from tests of equipment withdrawn from use:

- external appearance;
- operation of self-closing and self-locking gates; and
- strength.

The external appearance of all connectors tested was assessed after conditioning in simulated corrosive environments by subjective rating on a scale of 1–3, with higher scores corresponding to more advanced corrosion.

The correct operation and the force necessary to open the connector gate were assessed for all connector types.
Table 2. List of connector components sensitive to corrosion.

| Number | Class | Element                                    | Material                                      | Additional information |
|--------|-------|--------------------------------------------|-----------------------------------------------|------------------------|
| 1      | B     | Body                                       | Steel with zinc layer or aluminum alloy       | Figure 1               |
|        |       | Self-closing gate                          |                                               |                        |
|        |       | Self-locking gate                          |                                               |                        |
|        |       | Arm’s axis of turn and locking spring      |                                               |                        |
| 2      | M     | Body                                       | Steel with zinc layer or aluminum alloy       | Figure 2               |
|        |       | Self-closing gate                          |                                               |                        |
|        |       | Self-locking gate                          |                                               |                        |
|        |       | Arm’s axis of turn and locking spring      |                                               |                        |
| 3      | T     | Body                                       | Steel with zinc layer or stainless steel      | Figure 3(a)            |
|        |       | Self-closing gate                          |                                               |                        |
|        | T     | Self-locking gate                          |                                               |                        |
|        | with manual locking                       | Arm’s axis of turn and locking spring         | Steel with zinc layer or stainless steel      | Figure 3(b)            |
|        | with automatic locking                     | Body                                         |                                               |                        |
|        |       | Self-closing gate                          |                                               |                        |
|        |       | Self-locking gate                          |                                               |                        |
|        |       | Arm’s axis of turn and locking spring      |                                               |                        |
| 4      | A     | Body                                       | Steel with zinc layer or stainless steel      | Figure 4               |
|        |       | Self-closing gate                          |                                               |                        |
|        |       | Self-locking gate                          |                                               |                        |
|        |       | Arm’s axis of turn and locking spring      |                                               |                        |
| 5      | Q     | Body                                       | Steel with zinc layer or stainless steel      | Figure 5               |
|        |       | Screw                                      |                                               |                        |

before and after conditioning according to the procedure presented in Table 3. The force was measured on a ZWICK Z100W5A tensile testing machine (Zwick, Germany), with the connectors mounted in specially prepared holders.

The mechanical strength of the connectors was tested by loading of the connector until failure. The method of mounting the connector on the testing machine, the loading rate, etc., were selected according to Standard No. EN 362:2004.[3] The tests were carried out on the ZWICK Z100W5A testing machine. The force at failure before and after conditioning was tested and compared for particular connector types.

3.3. Conditioning: simulation of corrosive environments

Taking into consideration actual working conditions (corrosive environments), we decided to use simulated corrosive environments [7–9] using neutral salt spray (NSS), acid salt spray (ASS), and seawater mist, and methods simulating the development of intercrystalline, pitting, and stress corrosion (for stainless steel). The NSS method [10,11] is used for testing, e.g., metals and their alloys, certain metallic coatings (anodic and cathodic), and organic coatings on metallic materials for resistance to corrosion. It is also recommended by Standard No. EN 364:1992 [12] for corrosion resistance testing of standard personal equipment protecting against fall from a height. ASS is described in the literature [11–13] as a method simulating particularly aggressive corrosive environments. The methods of stainless steel testing simulating the development of pitting, stress, and intercrystalline corrosion are used for investigating this kind of corrosion in environments characterized by exposure to particularly aggressive chemical factors. Tables 4 and 5 present the types and parameters of the selected conditioning processes.

All of the connectors were conditioned whole to simulate real conditions of use.

3.4. Preparing connectors for testing

Prior to conditioning in a corrosive environment, the connectors were subjected to preliminary processing, which involved the removal of grease and impurities that could interfere with the access of corrosive factors to the metal elements. The procedure included the following:

- Mechanical removal of grease and impurities with a soft cloth.
- Washing with a soft brush in lukewarm water containing a mild detergent, then leaving to dry.
- Washing in acetone in an ultrasonic cleaner at 30°C for 15 min.
- Leaving to dry in a well-aerated place for 30 min.
Table 3. Procedure for testing the operation of connectors.

| Number | Class | Test method | Illustration |
|--------|-------|-------------|--------------|
| 1      | Q     | Manual checking of the possibility of turning the screw | ![Illustration](image1) |
| 2      | B     | Manual checking of:  
• turning the screw (a)  
• opening the gate (b)  
• return of gate to closed position (b) | ![Illustration](image2) |
| 3      | T     | Manual checking of:  
• the possibility of tightening the locking gate to the body of connector (a)  
• self-return of the locking gate to the exit position (a)  
• possibility of tightening the closing gate to the body of the connector (when locking gate is tightened too much) (b)  
• self-return of the closing gate to the exit position (b) | ![Illustration](image3) |

Note: **→** = direction of checking; **←** = reaction of object.

4. Results
Exposure to the corrosive conditions simulated with the aforementioned methods resulted in a number of hazardous effects in the tested connectors. Two types of deposits visible on connector elements were most evident:

- Grayish-white deposits formed as a result of the corrosion of the protective zinc coating of aluminum alloys (G in Table 6), rated on a 1–3 scale of intensity (according to subjective visual assessment).
- Reddish-brown deposits formed as a result of steel corrosion (R in Table 6), rated on a 1–3 scale of intensity (according to subjective visual assessment).

After a given duration of conditioning, the connectors were left to dry for approximately 1 h for the corrosion products to fix, then washed to remove loose particles and substances inducing corrosion, and left to dry.

The formation or absence of deposits depended on the connector type, corrosive environment, connector alloy, and duration of conditioning. Table 6 presents the results.

The corrosion of zinc protective coatings manifested itself by dulling and darkening of the connector surface as well as by the development of a white deposit. Figure 6 presents examples of corrosion processes over time in class B connectors conditioned with NSS, ASS, and seawater mist. Figure 7 presents corrosion processes over time in class T aluminum connectors conditioned with the NSS method. Figure 8 presents examples of the effect of...
### Table 4. Chemical substances used for conditioning and parameters of the conditioning process: conditioning method for equipment used in a non-aggressive environment.

| Method                          | Type of sprayed substance | Conditions and course of conditioning | Duration (h) |
|--------------------------------|---------------------------|---------------------------------------|--------------|
| Neutral salt spray (NSS)       | Solution of NaCl with concentration of 50 g/L, pH 6.5–7.2 | Substance sprayed in a continuous way with efficiency of 1–2 ml/h (efficiency measured on surface 80 cm²) Temperature in chamber of 35°C | 15–96        |
| Acid salt spray (ASS)          | Solution of NaCl with concentration of 50 g/L with addition of ice vinegar acid in quantity guaranteeing pH 2.6–3.3 |                                         |              |
| Seawater mist                  | Solution according to standard [14]                         |                                         |              |

### Table 5. Chemical substance used for conditioning and parameters of the conditioning process: conditioning method for equipment made from stainless steel for use in highly aggressive environments.

| Number of method | Test method | Type of chemical substance | Application | Duration (h) |
|------------------|-------------|---------------------------|-------------|--------------|
| 1                | HCl with addition of FeCl₃ at raised temperature | Solution of 10.8% FeCl₃ dissolved in 0.05 normal HCl | Test of resistance to pitting corrosion | 7–240        |
| 2                | HNO₃ and HF acid | Solution made with 100 ml HNO₃ (70%), 60 ml HF acid (50%) and adding distilled water to volume 1 L | Test of resistance to intercrystalline corrosion | 2–12         |
| 3                | Boiling HCl with addition of magnesium chloride | Solution of 42% magnesium chloride or 60% magnesium chloride leavened with HCl to pH 4 | Test of resistance to stress corrosion | 5–15         |

### Table 6. Changes in connector appearance dependent on conditioning type.

| Number | Class | Type of conditioning | Visual effects |
|--------|-------|----------------------|----------------|
|        |       |                      | Duration 24 h | Duration 48 h | Duration 72 h |
| 1      | B     | NSS                  | G-2, R-0      | G-3, R-0      | G-3, R-1      |
|        |       | ASS                  | G-1, R-1      | G-1, R-1      | G-2, R-3      |
|        |       | Seawater mist        | G-1, R-0      | G-1, R-0      | G-1, R-0      |
| 2      | T     | NSS                  | G-2, R-0      | G-2, R-0      | G-2, R-1      |
|        |       | ASS                  | G-1, R-0      | G-1, R-1      | G-1, R-1      |
|        |       | Seawater mist        | G-1, R-0      | G-1, R-0      | G-1, R-1      |
|        |       | T with manual locking| G-3, R-0      | G-3, R-0      | G-3, R-2      |
|        |       | NSS                  | G-1, R-1      | G-2, R-2      | G-2, R-3      |
|        |       | ASS                  | G-1, R-0      | G-1, R-0      | G-1, R-1      |
|        |       | Seawater mist        | G-1, R-0      | G-1, R-0      | G-1, R-1      |
| 3      | Q     | NSS                  | No visual effect of conditioning |              |              |
|        |       | ASS                  |               |              |              |
|        |       | Seawater mist method for SS |               |              |              |

Note: NSS = neutral salt spray; ASS = acid salt spray; SS = stainless steel; G = grayish-white deposit, rated on a 1–3 scale; R = reddish-brown deposit, rated on a 1–3 scale; 0 = no deposit.

NSS conditioning (for 72 h) on all of the tested types of connectors.

A longer duration of conditioning led, amongst other factors, to the corrosion of the base material of connectors, rivets, and springs. In addition to superficial corrosion changes, the springs used for self-closing of the mobile element were observed to fail in some connectors.

For class Q connectors made of stainless steel, the effects of conditioning were not visible by the unaided eye.
Neither superficial loss of shine nor any corrosion deposits were observed. Corrosive changes affecting connector elements affected the operation of the equipment. Manual tests demonstrated that the deposition of corrosion products, both on protective zinc coatings and the underlying steel, increased friction resistance in the mobile elements. In practice, this was manifested by the following:

- impaired unlocking and opening of the connectors; and
- operational failure of the self-closing gate.

The deposition of corrosion products on the elements of the locking mechanism, on the gate axle, and between the gate and the connector body (Figures 9, 10) can be regarded as the main cause of the observed effects.
The effects of corrosion product accumulation on the operation of particular connector elements were assessed on the following scale: A, no impairment of manual operation in comparison with non-conditioned connectors; B, slight impairment of manual operation; C, significant impairment of manual operation; P, automatic return to baseline position; and BP, no automatic return to baseline position. Table 7 presents the results of these tests.

The tests showed that the following:

- Extended duration of conditioning was associated with an increased amount of corrosion products on protective zinc coatings (in the form of a grayish-white deposit).
- The greater the damage of the protective zinc coating, the greater the visual effects of corrosion on the base material (steel).
- In class T connectors, corrosion of the base material in steel rivets and connector bodies made of aluminum alloy was observed after 72 h of conditioning.
- Accumulation of corrosion products on protective zinc coatings in class B connectors considerably impaired the tightening and loosening of the locking nut.
- Automatic locking failure in class B connectors, observed after conditioning for 48 h and longer, was particularly dangerous.
- In class T connectors with a manual-locking gate, made of aluminum alloy, no significant changes
Figure 9. Influence of corrosion on functioning of closing gates class B connectors: (a) closed and unlocked connector; (b) unclosed and locked connector. Note: arrows indicate places sensitive to corrosion.

in gate operation owing to corrosive changes were observed.

To assess the effect of corrosion on the operation of connectors, the force necessary to open the connector gate was measured for various types and durations of conditioning. The largest amounts of corrosion products accumulated on the connectors conditioned with the NSS method. In this case, the observed differences in force values required for opening the mobile element were most significant. Three samples of each connector type were used in the tests. Figures 7–10 present examples of results obtained for class B and class T connectors following different duration of NSS conditioning.

Opening force testing (figures 11–14) for class B and T connectors demonstrated a marked increase in that force even after a short duration of conditioning and the appearance of the first corrosion product (from 5 N for no conditioning to 45 N after 48 h conditioning and 70 N after 72 h conditioning for class T connectors). A further increase in duration of conditioning did not cause a proportional increase in opening force. On the other hand, the results became more dispersed (e.g., 7–21 N after 96 h conditioning for class B connectors and 7–55 N after 96 h conditioning for class T connectors).

The effect of corrosion on the mechanical strength of the connectors was also studied. The tests involved measurement of force at failure. The results obtained after the longest conditioning for class B, T, and Q connectors for the NSS, ASS, and seawater mist conditioning methods did

Table 7. Assessment of the effect of corrosion product accumulation on the mobility of locking elements of the connectors.

| Conditioning | NSS  | ASS  | Seawater mist | Methods for SS |
|--------------|------|------|---------------|----------------|
| Duration (h) | 48   | 96   | 48            |                |
| Turn of the blocking sleeve | B C C C C B C C C C A B A A A A B A B | T T B B T T |
| Automatic return of the blocking sleeve | P BP P P P BP BP P BP P BP P | T T B B Q T |
| Dislocation of the locking gate | A A A A A A A A A | T B B B B T |
| Automatic return of the locking gate | P P P P P P P P P | B B B B B Q |

Note: =does not apply; NSS = neutral salt spray; ASS = acid salt spray; SS = stainless steel; Scale: A = no impairment of manual operation in comparison with non-conditioned connectors; B = slight impairment of manual operation; C = significant impairment of manual operation; P = automatic return to baseline position; and BP = no automatic return to baseline position.
Figure 10. Influence of corrosion on functioning of closing gates in class T connectors with automatic locking: (a) closed and unlocked connector; (b) unclosed and unlocked connector. Note: arrows indicate places sensitive to corrosion.

Figure 11. Courses of unlocking force connector’s gate class B connector with automatic locking.

Figure 12. Courses of unlocking force connector’s gate class B connector with manual locking.

Figure 13. Courses of unlocking force connector’s locking gate T class connector with automatic locking.

Figure 14. Courses of unlocking force connector’s closing gate T class connector with automatic locking.

Table 8. Tension break force obtained for new connectors and after 96 h conditioning.

| Class | New connector (kN) | NSS (kN) | ASS (kN) | Seawater mist (kN) |
|-------|--------------------|----------|----------|--------------------|
| B     | 29.1 (1.26)        | 28.3 (2.06) | 28.8 (1.94) | 30.0 (1.41)        |
| T     | 28.2 (1.57)        | 28.7 (1.32) | 26.5 (2.03) | 27.1 (1.88)        |
| Q     | 37.0 (1.18)        | 36.1 (2.11) | 35.6 (1.43) | 37.3 (1.26)        |

Note: NSS = neutral salt spray; ASS = acid salt spray.

not demonstrate significant changes in the force at failure (Table 8).

Significant loss of mechanical strength was observed for class Q connectors made of stainless steel conditioned with method 1 (in HCl with FeCl3; see Table 5) for 240 h and for class B connectors made of carbon steel with a brass safety nut conditioned with the ASS method for 96 h. Table 9 presents these results.
In most cases of conditioning, even the longest, mechanical strength tests of connectors demonstrated no significant change for carbon steel and aluminum, in contrast to stainless steel (class Q). Despite the fact that conditioning did not have any effect on the appearance and functionality of connectors, it could still cause a significant loss of strength owing to pitting or intercrystalline corrosion (Table 9). Another instance of considerable mechanical strength loss was found for class B connectors with a brass safety nut. This metal underwent significant degradation as a result of conditioning, which weakened the structure of the whole connector.

5. Conclusions

The following conclusions were drawn concerning both the immediate results of laboratory tests and their consequences affecting the safety of users of connectors as components of personal equipment protecting against falls from a height.

Exposure to a corrosive environment may result in the following:

- Corrosion of the protective coating on the base metal in connectors. Corrosion of this type can limit the functionality of the connector and make it more difficult to operate, e.g., by increasing its resistance to closing, opening, and locking. This may lead to connection failure due to a non-closed connector, or the opening of a non-locked one (e.g., as a result of loss of the self-locking function), which has a direct impact on user safety.

- Corrosion of the base material. In such cases, corrosion of connectors, especially those made of stainless steel (e.g., class Q connectors), can lead to considerable loss of their mechanical strength and potential failure in case of overloading. This is particularly dangerous because the users are unable to detect such corrosion with the unaided eye. Corrosive changes, even those that are relatively small, can considerably impair the strength and operation of connectors made of other types of steel and non-ferrous metal alloys. The most serious hazards associated with the corrosion of the base material include fracture of any load-bearing element of the connector (e.g., the body), and, consequently, failure of the protective system to arrest a fall from a height.

To date, tests and assessments of connector conformity with the requirements of Directive 89/686/EEC have been based on Standard No. EN 362:2004.[3] This standard discusses only one type of corrosive environment for connector testing. Taking into consideration the results presented in this article, this is highly insufficient, especially when these elements are to be used in aggressive corrosive environments.

The hazards described indicate unequivocally that the problem of corrosion is so important in the case of connectors that it should be solved at three levels: equipment manufacturers, notified bodies responsible for type assessment, and users.

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No potential conflict of interest was reported by the authors.

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