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Selecting materials for fastening screws for metal members and sheeting

Dedicated to Prof. Dr.-Ing. *Helmut Saal* on the occasion of his 70th birthday

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This paper deals with the parameters for choosing the materials for fastening screws used in connections involving thin-walled sections and thin sheeting. Different types of corrosion processes and repeated bending due to thermal elongation are identified as the most important parameters; these are explained in detail here. Based on that, some general recommendations for choice of material are given.

1 Introduction

Thin-walled building components such as trapezoidal and corrugated profiled sheeting, cassettes (liner trays) and sandwich panels as well as cold-formed sections are typically fixed by thread-forming screws: on the one hand, self-tapping screws, where pre-drilling is necessary, and on the other hand, self-drilling screws, where drilling and thread-forming are combined in one operation. Most fastening screws (usually referred to simply as "screws") are made from stainless steel or zinc-plated carbon steel.

Since the aforementioned building components mostly involve external walls or roofs exposed to the weather, washers with a scorched EPDM sealing (so-called sealing washers) or EPDM sealing rings are necessary. The metallic part of the sealing washers is made from stainless steel, carbon steel or aluminium.

Selecting materials for fastening screws and washers must take into account safety (durability and loadbearing capacity of corroded fasteners, resistance of fasteners to repeated bending caused by thermal movement) and aesthetics aspects. The latter aspect is important because thin sheeting is often used for façades, and corrosion products will affect the appearance.

This paper provides some guidance on choice of materials for fastening screws in connection involving thin-walled sections and thin sheeting. The guidance is based on [1] and the authors' own experience as experts in liability cases, amended by the results of tests, some of which have already been published in [2]. The paper can be seen as an addendum to [3] and [4], which do not cover this topic.

Although this information primarily concerns screws, in principle, it can be transferred to related types of fasteners such as blind rivets and powder-actuated pins.

2 Fastening screws

2.1 Preliminary remarks

Fig. 1 shows several examples of typical fastening screws. Most of them have a sealing washer, one a sealing ring. As it is quite usual, the one with the sealing ring has a mushroom head, whereas all the others have hexagonal heads. The self-drilling screw is also shown with a shank (i. e. unthreaded portion), which is used, for example, for crest fixings or fixing sandwich panels. In the case of sandwich panels, screws with an additional thread under the head are very often used, the intention of which is to help achieve a watertight connection.

2.2 Materials

2.2.1 Carbon steel

Carbon steel screws are usually made of case-hardened or heat-treatable steel [5]. Steel grade 1.1147 is a quite common material. Owing to the heat treatment, carbon steel fasteners attain a high strength with surface hardness values of about

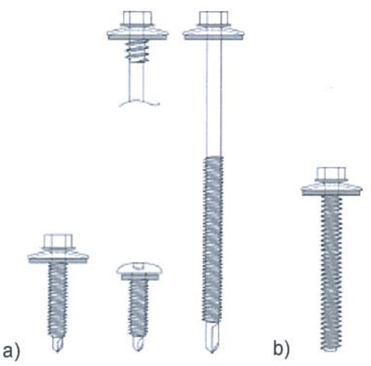

Fig. 1. Fastening screws: a) self-drilling screws, b) self-tapping screw

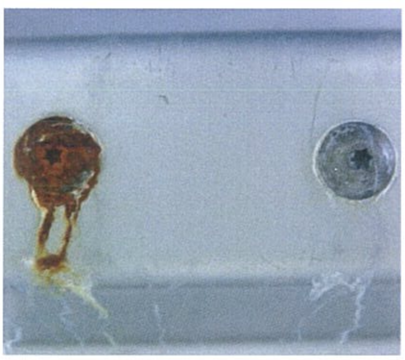

Fig. 2. Screws after neutral salt spray test: carbon steel screw (left) and austenitic stainless steel (right)

530 HV0.3 and core hardness values of 320–400 HV10. However, these high hardness values are accompanied by the risk of hydrogen embrittlement.

Carbon steel screws must be protected against corrosion. The most common type of corrosion protection is galvanic zinc plating to EN ISO 4042 [6]. It should be pointed out that fasteners listed in a European technical approval usually have a zinc coating specified as A3K, which means that the fasteners are zinc-plated with a coating thickness ≥ 8 μm and passivated; the usual standard is just A2K with a coating thickness ≥ 5 μm. Hot-dip galvanizing of such screws is not possible because the thick layers of zinc would clog the threads.

Zinc flake coating systems with products such as Ruspert and Dural are also used. These coatings have an organic or inorganic matrix with dispersed zinc and aluminium particles. Unfortunately, these coatings may be damaged during transport or by abrasion during installation, possibly even scraped off. It is therefore difficult to assess such coatings.

2.2.2 Stainless steel

2.2.2.1 Preliminary remarks

Stainless steels for screws can be classified according to the system given in EN ISO 3506-4 [7], which specifies property classes (20H to 40H, corresponding to 200–400 HV10). The property classes that can be achieved depend on the steel group (austenitic, martensitic or ferritic stainless steel). Stainless steels achieve their corrosion resistance through a passive layer of chromium oxide.

2.2.2.2 Austenitic stainless steel

Designations such as steel grades A2 and A4 for austenitic stainless steels are quite familiar and refer predominantly to the corrosion resistance. According to EN ISO 3506-4, austenitic stainless steels for screws contain 15–20 % chromium and 8–19 % nickel. Austenitic stainless steel A4 also contains a significant amount of molybdenum (2–3 %). Austenitic stainless steels cannot be hardened by heat treatment, but by cold working. Increasing the surface hardness by nitriding is also possible. If self-drilling screws for drilling into steel are required, a drill-point made of hardened carbon steel has to be welded to the tip of the screw. After installation, only the stainless steel part of the screw should form part of the loadbearing system, and not the welded drill-point. Drilling into aluminium is possible with drill-points made of stainless steel.

2.2.2.3 Martensitic stainless steel

According to EN ISO 3506-4, martensitic stainless steels for screws contain 11.5–18 % chromium. Martensitic stainless steels can be heat treated, which allows the production of self-drilling screws in one piece complete with a drill-point (i.e. does not have to be welded on). Corrosion resistance is considerably lower than for austenitic stainless steel and their high hardness after heat treatment makes them vulnerable to hydrogen embrittlement and stress corrosion cracking.

2.2.2.4 Ferritic stainless steel

According to EN ISO 3506-4, ferritic stainless steels for screws contain 15–18 % chromium. Ferritic stainless steels cannot usually be heat treated. They do not play a significant role in loadbearing connections involving thin-walled building components, so will not be considered in the following.

2.2.3 Aluminium

Screws made of aluminium usually consist of wrought aluminium alloys 6000 or 7000. As they are rather soft, applications for aluminium for screws are limited to, for example, self-tapping screws for fixing sheets to timber supporting structures. Aluminium achieves its corrosion resistance through a passive layer. Up to now, no ETA for screws made of aluminium has been published; therefore, they will not be dealt with here.

2.3 State of the art in regulations

European technical approvals (ETAs) for screws have been available since 2010. The approvals specify characteristic resistance values for different loading situations depending on type of fastener, material, thickness of components to be connected, etc.

Regarding corrosion protection, the information given in the ETAs is rather weak, and expressed as follows:

> "The intended use comprises fastening screws and connections for indoor and outdoor applications. Fastening screws that are intended to be used in external environments with high or very high corrosion category according to the standard EN ISO 12944-2 should be made of stainless steel."

and

> "Fastening screws completely or partly exposed to external weather or similar conditions are made of stainless steel or are protected against corrosion. For the corrosion protection the rules given in EN 1090-2:2008+A1:2011, EN 1993-1-3:2006+AC:2009 and EN 1993-1-4:2006 are taken into account."

The formulation in the ETAs has to respect the different traditions in European countries. Whereas some countries have banned carbon steel fasteners from applications in external environments or applications with comparable moisture conditions, others have not, or have no regulations at all.

The current ETAs do not refer directly to the informative Annex B of both EN 1993-1-3 [8] and EN 1999-1-4 [9], which gives further recommendations on choice of material. But in general, for the corrosion protection of the screws, the information given there should be taken into account. Table 1 gives recommendations for the preferred screw materials depending on the materials of the components and the corrosivity of the environment. The corrosivity of the environment is classified by referring to the corrosivity categories of EN ISO 12944-2 [10] (Table 2), which of course do not take into account the microclimate (locally increased moisture, concentration of salts, etc.). More strenuous requirements might be necessary for specific situations and construction details, e. g. if screws are posi-

Table 1. Fastener material with regard to corrosion environment according to EN 1993-1-3 and EN 1999-1-4 (abbreviated and edited)

Corrosivity category	Sheet material	Material of fastener			
		Aluminium	Electrolytically galvanized steel, coating thickness ≥ 8μm	Stainless steel, case-hardened, 1.4006 (C1)	Stainless steel, 1.4301 (A2)
C1	A, B, C	×	×	×	×
	D, E, S	×	×	×	×
C2	A	×	–	×	×
	C, D, E	×	–	×	×
	S	×	–	×	×
C3	A	×	–	–	×
	C, E	×	–	(×)	(×)
	D	×	–	–	(×)
	S	–	–	×	×
C4	A	×	–	–	(×)
	D	–	–	–	(×)
	E	×	–	–	(×)
	S	–	–	–	×
C5-I	A	×	–	–	(×)
	D*)	–	–	–	(×)
	S	–	–	–	×
C5-M	A	×	–	–	(×)
	D*)	–	–	–	(×)
	S	–	–	–	×
Abbreviations and footnotes					
A	Aluminium irrespective of surface finish	×		Type of material recommended from corrosion standpoint	
B	Uncoated steel sheet	(×)		Type of material recommended from corrosion standpoint under the specified condition only, insulation washer of material resistant to ageing between sheeting and fastener	
C	Hot-dip zinc-coated (Z275) or aluzinc-coated (AZ150) steel sheet				
D	Hot-dip zinc-coated plus organic coating				
E	Aluzinc-coated (AZ185) steel sheet	–		Type of material not recommended from corrosion standpoint	
S	Stainless steel	*)		Always check with sheet supplier	

Table 2. Atmospheric corrosivity categories according to EN ISO 12944-2 [10] and examples of typical environments

Corrosivity category	Corrosivity level	Examples of typical environments in temperature climate (informative)	
		Exterior	Interior
C1	very low	–	Heated buildings with clean atmospheres, e.g. offices, shops, schools, hotels.
C2	low	Atmospheres with low level of pollution. Mostly rural areas.	Unheated buildings where condensation may occur, e.g. depots, sport halls.
C3	medium	Urban and industrial atmospheres, moderate sulphur dioxide pollution. Coastal areas with low salinity.	Production rooms with high humidity and some air pollution, e.g. food-processing, plants, laundries, breweries, dairies.
C4	high	Industrial areas and coastal areas with moderate salinity.	Chemical plants, swimming pools, coastal shipyards and boatyards.
C5-I	very high (industrial)	Industrial areas with high humidity and aggressive atmospheres.	Buildings and areas with almost permanent condensation and with high pollution.
C5-M	very high (marine)	Coastal and offshore areas with high salinity.	Buildings and areas with almost permanent condensation and with high pollution

tioned in cavities or voids. This is the case with external wall claddings with a ventilation cavity, or with roofs and façades in the form of multi-layer shells where corrosive agents could accumulate and moisture could infiltrate.

Table 1 does not cover screws with zinc flake or similar coatings because of the different properties of the coatings available. Experience with such coated screws for flat roof systems tested according to ETAG 006 [11] has revealed the vulnerability of the coatings.

In addition, it must be mentioned that according to these informative annexes, unprotected screws made of steel without zinc plating may be used in corrosivity category C1. In fact, this results in the same application range and assumed corrosion resistance for both zinc-plated and unprotected screws!

3 Types of corrosion

3.1 Atmospheric corrosion (general corrosion)

Atmospheric corrosion is the development of a uniform layer of oxide (rust) on carbon steel screws under the influence of neutral water or a humid atmosphere. Pollution will increase the corrosion problem. Atmospheric corrosion can be found in nearly all applications for fastening screws in roofs and walls. Atmospheric corrosion leads to a reduction in cross-section, thus a reduction in the loadbearing capacity of the connection. As rust develops, so the aesthetics are also affected – and not only the screw itself: rusty draining water can also stain façade or roof sheets. In cases where the washers are affected, too, leakage may become a problem.

Corrosion by aeration cells is a special case of atmospheric corrosion in areas with oxygen deficiency. Examples are screws passing through wet insulation materials or seam fasteners with capillary moisture between the sheets. Examples of damage can be found in [1].

3.2 Galvanic corrosion (bimetallic corrosion)

Galvanic corrosion occurs when two metals with a sufficiently different electrode potential (expressed by their positions in the electrochemical series) come into contact in the presence of an electrolyte (e. g. moisture from rain). An electric current is generated by the difference in the electric potential. The current causes the less electropositive metal (anode) to corrode by the dissolution of ions. Electrons react with hydrogen ions and form atomic or molecular hydrogen, evolving at the cathode.

Important parameters are the relative positions of the two metals in the electrochemical series and therefore their potential difference, which depends on the type of electrolyte. It is important to distinguish between the standard potential (determined with the standard hydrogen electrode) and the practical potential, e. g. in seawater or acidic water. Another important parameter is the ratio of surface of cathode and anode. Potential differences become less problematic if the surface ratio of anode to cathode is high.

That is why stainless steel or aluminium fasteners shall be used for fixing aluminium sheets or aluminium components in general. If carbon steel fasteners are to be used, the thin layer of galvanic zinc plating would be eroded within a shorts time but the remaining carbon steel fastener would not be affected due to the higher position of steel in the electrochemical series compared with aluminium. From then on the protective effect of the zinc is missing. On the other hand, using aluminium fasteners for fixing steel sheet is not recommended from the point of view of galvanic corrosion. The surface ratio of cathode (base metal carbon steel) to anode (less noble metal aluminium) is low, leading to an accelerated rate of corrosion. Aluminium fasteners could be used for fixing aluminium parts to aluminium supporting structures. As fasteners made from aluminium are not that common and have other disadvantages, only stainless steel fasteners should be used for fixing aluminium components in areas with at least a slight likelihood of electrolytes occurring. Otherwise, the use of stainless steel fasteners in aluminium components in severe maritime environments leads to severe corrosion of the aluminium adjacent to the fasteners due to the aggressive electrolyte. Here, the connection should be shielded from the influence of seawater by coating, grout, etc. The consequences range from spoiling the appearance of façades and structures to failure of the connection due to a reduction in the cross-section of the corroded fastener if bimetallic corrosion is not taken into account sufficiently.

3.3 Hydrogen embrittlement

Hydrogen embrittlement describes the reduction in ductility and the subsequent brittle fracture of metals caused by hydrogen. Recombination of atomic hydrogen diffusing into the metal, especially at the grain boundaries, causes pressure in cavities and tensile stresses in the atomic lattice of the metal matrix. Owing to these stresses, the term "hydrogen-induced stress corrosion cracking" is also used. The term "cathodic stress corrosion cracking" refers to the electrochemical process.

Tensile stresses (e. g. residual stresses from cold forming, but also tensile stresses from tightening) increase susceptibility because of lattice deformation, which eases the diffusion of hydrogen into the steel and its most highly stressed parts. Non-alloy steels such as the ferritic carbon steels with tensile strengths of about 1000 N/mm^2 or hardness values above 320 HV10 are prone to hydrogen embrittlement. These steel grades are typically used for screws. Martensitic steels with high strength values are also prone to hydrogen embrittlement [12], whereas austenitic (stainless) steels are not affected.

Sources of hydrogen are production processes such as pickling prior to galvanic plating (primary hydrogen embrittlement, delayed brittle fracture). EN ISO 4024 gives recommendations for mitigating hydrogen embrittlement. The options comprise stress relieving or tempering, which of course can only be applied during production. But the standard also states that complete elimination of hydrogen embrittlement cannot be assured.

Hydrogen can also evolve from corrosion processes, e. g. from galvanic corrosion (secondary hydrogen embrittlement). A typical example of a brittle failure of a screw by hydrogen embrittlement is fixing an aluminium sheet to a steel structure with a carbon steel screw. Exposure to weathering leads to galvanic corrosion (rain as electrolyte) with the release of atomic hydrogen. The thin layer of zinc coating is not diffusion-resistant to hydrogen or may even have been already damaged during installation or the corrosion

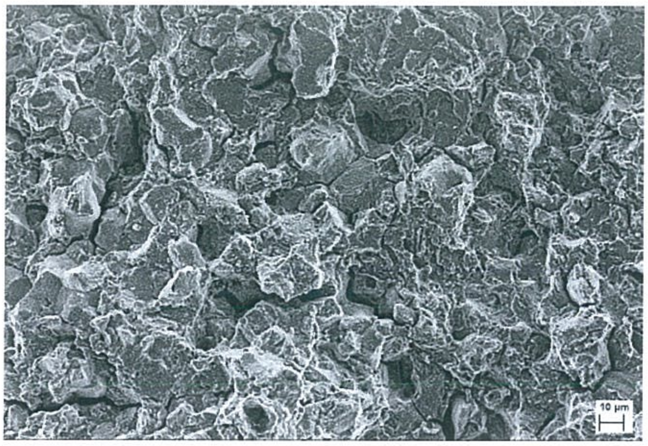

Fig. 3. Fracture surface of a screw after failure due to hydrogen embrittlement

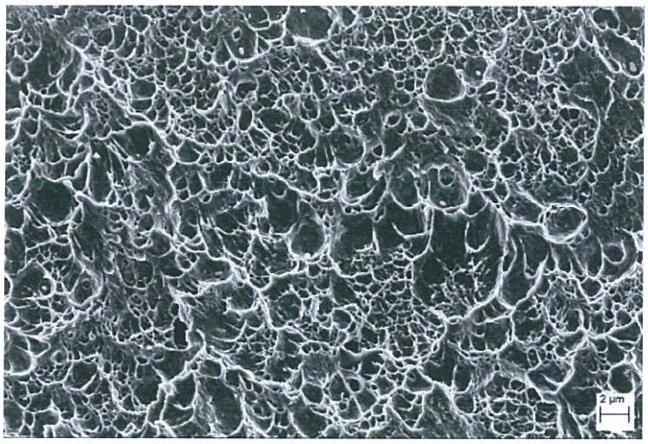

Fig. 4. Fracture surface of a screw after overtightening (ductile fracture)

process. The hydrogen diffuses into the screw, especially at the grain boundaries, and accumulates at the most highly stressed parts (usually at the radius between shank and head). Brittle failure will occur in the shank near the head. Fig. 3 shows a typical fracture surface – the splits at the grain boundaries can be seen well. For comparison, Fig. 4 shows a fracture surface after a ductile failure.

3.4 Stress corrosion cracking

Stress corrosion cracking (or "anodic stress corrosion cracking") as it will be discussed here is a form of corrosion of ferritic, austenitic and martensitic stainless steels under the influence of chloride, acidic or oxidizing electrolytes. It also results in a reduction in ductility and resistance, leading to a brittle intergranular or transgranular failure. Mechanical tensile stresses (e. g. residual stresses from cold forming, but also tensile stresses from tightening or from external loads) increase susceptibility. Depending on the electrolyte, increased ambient temperatures might be necessary for failure. Usually, stress corrosion cracking and its consequences are not of importance for the applications of screws discussed here.

3.5 Pitting corrosion

Pitting corrosion is a highly localized form of corrosion that can be found in stainless steel or aluminium. In principle, there are two reasons for pitting corrosion: as local damage to the passive layer of, for example, stainless steel or aluminium, or as galvanic corrosion of single grains or precipitation of a base metal (e.g. an alloying element) in the surrounding noble metal.

Usually, pitting corrosion and its consequences are not of importance for the applications of screws discussed here.

3.6 Crevice corrosion

Crevice corrosion is a localized form of attack that is initiated by the differences in the oxygen levels between the creviced and exposed regions. Crevices occur around the threads of the fastening screws and the components being connected. It is not likely to be a problem except in stagnant solutions where a build-up of chlorides can occur. The severity of crevice corrosion very much depends on the geometry of the crevice: the narrower and deeper the crevice, the more severe the corrosion. In principle, pitting and crevice corrosion are similar phenomena, but the attacks start more easily in a crevice than on an open surface.

4 Governing parameters for choosing materials regarding corrosion

Fastener materials must be selected depending on the materials of the structural parts to be connected, the stressing by corrosivity of the surroundings and the intended life cycle. The most important point is corrosion which is also influenced by the materials of the parts to be connected. It must be pointed out that the high strength of the fasteners does not have a significant effect on the resistance of the connection because with thin-walled sections and thin sheeting, failure of the building components being connected is the governing parameter. Stresses due to forces therefore do not normally become critical for the choice of material for fasteners.

Corrosivity of the surroundings depends on moisture conditions, air pollution (dust, which may dissolve in water, chloride in industrial and marine environments or from road de-icing salts, sulphur dioxide emitted from power plants and traffic, etc.) and period of exposure. Moisture may gain access to the screws by way of weather conditions, but also via condensation at thermal bridges. Some thermal insulation materials such as mineral wool can work like a sponge, absorbing water. If screws are installed through a sandwich panel containing saturated mineral wool, corrosion directly affects the loadbearing part of the screw. It is also important to realize that conditions may get worse as corrosive agents accumulate. One prominent example is the accumulation of both corrosive agents such as de-icing salts and moisture behind external walls with a ventilation cavity. On the other hand, occasional rain may even have a cleaning effect on the screw. So detailing is also a very important parameter.

5 Bending of fasteners under repeated loading

Different temperatures in the connected components (e. g. between a trapezoidal profiled sheet panel in a façade heated by the sun and a section of the supporting struc-

Table 3. Choice of corrosion resistance class according to German national approval Z-30.3-6

Exposure	Exposure class		Criteria and examples	Corrosion resistance class			
				I	II	III	IV
Humidity, yearly average value U of humidity	SF0	dry	U < 60 %	×			
	SF1	seldom moist	60 % ≤ U < 80 %	×			
	SF2	often moist	80 % ≤ U < 95 %	×			
	SF3	permanent moist	95 % < U		×		
Chloride content of surrounding area, distance M from the sea, distance S from busy roads with road salt application	SC0	low	rural, urban, M > 10 km, S > 0.1 km	×			
	SC1	medium	industrial area, 10 km³ M > 1 km, 0.1 km³ S > 0.01 km		×		
	SC2	high	M ≤ 1 km S ≤ 0.01 km			×[1]	
	SC3	very high	indoor swimming pool, road tunnel				×[2]
Exposure to redox-affecting chemicals (e. g. SO2, HOCl, Cl2, H2O2)	SR0	low	rural, urban	×			
	SR1	medium	industrial area			×[1]	
	SR2	high	indoor swimming pool, road tunnel				×[2]
pH-value on surface	SH0	alkaline (e. g. with contact to concrete)	9 < pH	×			
	SH1	neutral	5 < pH ≤ 9	×			
	SH2	low acidic (e. g. with contact to wood)	3 < pH ≤ 5		×		
	SH3	acidic (exposure to acids)	pH ≤ 3			×	
Location of structural parts	SL0	indoors	indoors, heated and not heated	×			
	SL1	outdoors, exposed to rain	exposed structures		×[3]		
	SL2	outdoors, accessible but protected from weather	roofed structures		×[3]		
	SL3	outdoors, non-accessible4), ambient air has access	accumulation of pollutants on surface by air pollution, cleaning not possible			×	

Only the exposure leading to the highest corrosion resistance class (CRC) has to be taken into account.
No higher requirements result from the coincidence of exposure conditions.
Contaminated steel surfaces (e.g. paint, grease, dirt) may lead to lower corrosion resistance.

1) If accessible structures are cleaned regularly or exposed to rain, corrosion will be much lower and the CRC may be reduced by one class. Otherwise the CRC has to be increased by one class if corrosion-relevant substances can be deposited on and remain on the surfaces of structural parts.
2) If accessible structures are cleaned regularly, corrosion will be much lower and the CRC may be reduced by one class.
3) If the life cycle is limited to 20 years and pitting corrosion up to 100 mm is tolerated, CRC I may be chosen (no visual demands).
4) Structures are classified as non-accessible if an inspection of their condition is extremely difficult and a necessary rehabilitation is very expensive.

ture) and resulting differences in thermal elongation may lead to additional stresses in the fasteners. In fixings where both components are directly adjacent to each other, the stresses will lead to shear forces in the fastener and to an elongation of the holes in the components. Otherwise, the distance between the components being connected will lead to additional bending stresses in the fastener. This is the case for crest fixings in trapezoidal profiled sheeting and for sandwich panel fixings, where the screw passes through both faces of the panel. If thermal elongation changes repeatedly from day to night, the bending stresses in the fasteners will also be repeated. This has to be taken into account when designing the fasteners, e. g. according to [4].

The resistance of the connection to repeated bending, expressed by the allowable head deflection max. u, depends on the thickness t_{II} of the supporting structure and the corresponding degree of rotational restraint provided by that structure. Whereas for smaller thicknesses t_{II}, local deforma-

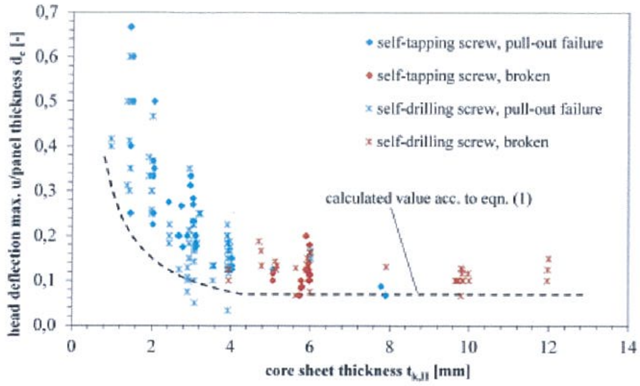

Fig. 5. Allowable value for head deflection of austenitic stainless steel screws [2]

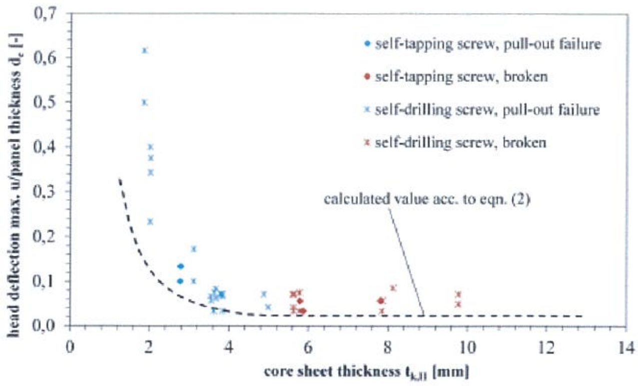

Fig. 6. Allowable value for head deflection of carbon steel screws

Table 4. Allocation of steel grades to corrosion resistance classes

No.	Steel name 1)	Steel grade 1)	Steel grade 2)	Type of stainless steel 3)	Corrosion resistance class CRC 4)
1	X2CrNi12	1.4003	not suitable for fastening elements	F	I / low
2	X6Cr17	1.4016		F	
3	X5CrNi18-10	1.4301	A2	A	II / medium
4	X2CrNi18-9	1.4307	A2L	A	
5	X3CrNiCu18-9-4	1.4567	A2L	A	
6	X6CrNiTi18-10	1.4541	A3	A	
7	X2CrNiN18-7	1.4318	5)	A	
8	X5CrNiMo17-12-2	1.4401	A4	A	III / high
9	X2CrNiMo17-12-2	1.4404	A4L	AF	
10	X3CrNiCuMo17-11-3-2	1.4578	A4L	A	
11	X6CrNiMoTi17-12-2	1.4571	A5	A	
12	X2CrNiMoN17-13-5	1.4439	5)	A	
13	X2CrNiN23-4	1.4362	5)	A	
14	X2CrNiMoN22-5-3	1.4462	5)	AF	IV / very high
15	X1NiCrMoCu25-20-5	1.4539	5)	A	
16	X2CrNiMoNbN25-18-5-4	1.4565	5)	A	
17	X1CrNiMoCuN25-20-7	1.4529	5)	A	
18	X1CrNiMoCuN20-18-7	1.4547	5)	A	

1) according to EN 10088-1
2) according to EN ISO 3506
3) F – ferritic steels; A – austenitic steels; AF – austenitic-ferritic steels
4) For choice of corrosion resistance class (CRC) see Table 3.
5) Actually not covered; therefore the steel grade according to EN 10088-1 should be used.

tion of the structure is the governing effect (allowing for large values u of deformation/deflection), for larger thicknesses t_{II}, full restraint is achieved and the effects of geometry and screw material dominate the resistance. Bending tests with fasteners under repeated loading have shown that stainless steel fasteners behave much better than carbon steel fasteners. Bending tests according to [4] were performed with austenitic stainless steel screws and carbon steel screws. Figs. 5 and 6 show the results of the tests. The maximum allowable value of head deflection max. u divided by the length of the cantilever (equal to the thickness d_c of a sandwich panel) is plotted against the thickness $t_{k,II}$, the core sheet thickness of the supporting structure. The results cover tests with different screws, both self-drilling and self-tapping, from different manufacturers. Statistical evaluation leads to the design curves given in the figures. The design curve for austenitic stainless steel fasteners can be written as

$$\text{max. } u = 0.3\,\text{mm} \cdot \frac{d_C}{t_{k,II}} \geq 0.07 \cdot d_C \qquad (1)$$

and for carbon steel fasteners as

$$\max.\ u = 0.1\,mm^2 \cdot \frac{d_C}{t_{k,II}^2} \geq 0.023 \cdot d_C \qquad (2)$$

Whereas max. u for smaller thicknesses $t_{k,II}$ does not depend that much on the material of the screw, material properties become important for larger thicknesses and higher degrees of rotational restraint. With greater thicknesses $t_{k,II}$, the allowable value max. u for the head deflection of austenitic stainless steel fasteners is three times as high as the value for carbon steel fasteners. The reason for this difference in behaviour is that the high hardness of case-hardened carbon screws prevents a reduction in critical stress peaks through local plastic deformation. Although head deflection is usually not critical for austenitic stainless steel screws, it must be checked carefully if carbon steel screws are to be used.

6 Recommendations and summary

The following recommendations are based on the effects described in sections 3 to 5 and are backed up by considerable experience on a national level:

- Screws completely or partly exposed to the weather or comparable moisture conditions should be made from austenitic stainless steel. This does not refer to welded drill-points, but it has to be checked that the screw-in length is large enough to ensure that carbon steel parts are not part of the loadbearing system.
- The length of the construction period should be taken into account, also with respect to the time of year of the construction works.
- Austenitic stainless steels of higher grades (e. g. A4) are necessary in applications where concentrations of corrosive agents may accumulate or in surroundings with higher corrosivity. This may be the case with screws in the ventilation cavities or voids of external walls or otherwise shielded from direct rain and where regular cleaning is not foreseen or not possible. Tables 3 and 4, published in [13], help the designer to select the right stainless steel grade with respect to the corrosion resistance of fastening elements.
- Screws made of carbon steel or martensitic stainless steel are not suitable in cases where minimum corrosion resistance requirements exist. Carbon steel screws, including electrolytically galvanized or coated fasteners, and screws made of martensitic stainless steel should only be used where moisture does not affect them. This covers:
  - fastening the inner shells of multi-shell roof and wall structures (decking profiles or cassettes) around dry and predominantly closed rooms provided the outer shell prevents the entry and accumulation of corrosive agents and rain (outer shell made of sheeting),
  - fastening the decking profiles of unventilated single shell roofs around dry and predominantly closed rooms with insulation on the outer side (typical flat roof applications with insulation membranes),
  - ceiling systems over dry and predominantly closed rooms.
- Fastening of aluminium sheeting should only be done with screws made of stainless steel (or aluminium) except in severe maritime environments, which require additional protection measures for the connections.
- Galvanic corrosion should be taken into account when designing and detailing structures.
- Although repeated bending of fasteners due to thermal elongation and movement is not usually critical for the design of austenitic stainless steel fasteners, care should be taken when using hardened martensitic or carbon steel screws.

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