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TESTING CONNECTIONS AND FASTENERS TO DETERMINE STRENGTH CHARACTERISTICS

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1. Introduction

The increasing number of product functions and maintenance requirements as well as the need for cheaper production puts large demands on the product structure, i.e. the layout of the product components and their connections. As a consequence, the number of requirements increases, making it increasingly difficult to manage conflicting aims. This is particularly true for maintenance and recycling requirements. These have become more and more important due to changed product strategies, other concepts of use, and new legislation. The disassembly of technical products as a key part of maintenance and recycling are substantially affected by the product structure, the connections within the product, and the design of the connected components. Warranty and product liability are also having a much greater impact on the design of technical products due to legislation concerning consumer rights.

When designing products it is necessary to choose the right connections, because the connection technology profoundly influences the manufacturing economics, maintenance and recycling effort, and significantly affects the reliability and safety of technical products. So, the connection technology is the "technologically most important and economically most significant production process in modern industry" [Bauer 1991, p1].

The paper focuses on the results of the tests used to analyse the strength characteristics of the connections in question. We do not focus here on the description of the methods used for analysation (for details see [Wünsche et al. 2005]).

2. Aims and Objectives

"Connections are an essential part of engineering. The technology begins primarily with the connecting." [Bauer 1980, pS82]. Without connections there are no functional and efficient technical systems. Complex products have a number of components which can fulfill their assigned tasks only when they are connected. Connections have to be efficient, reliable, safe and economic. The working loads, the resultant stresses as well as general, boundary and environmental conditions that are determined in the early stages of the product development process provide the information needed to select and design the correct connection. "But only if all necessary and obtainable information about the various influencing parameters is available in time during the respective stages of the design process, can this information be analysed with respect to the given task and used in an appropriate way." [Bauer 1987, p85]

To meet the various requirements and the many – sometimes contradictory – design aims, the design engineer needs sufficient knowledge about the characteristic features and peculiarities of connections. This knowledge is in short supply for most connections, in particular for the disassembly-supporting connections. These connections "support assembly, disassembly and recycling, but the lack of fundamental knowledge and quantitative properties required for dimensioning makes the access and

[thus] the (universal) application in the design process difficult" [Schmidt-Kretschmer 1994, p2]. The only available information about disassembly-supporting connections can be found in supplier brochures, catalogues and technical literature. The information there is mostly limited to geometric data, without details concerning strength, assembly and disassembly.

As a result of a comprehensive investigation of German standards and guidelines we found that no real standardisation exists, although "there is no better way to give the numerous industrial users a better and more effective understanding of the knowledge and opportunities of the whole connection technology than standards and guidelines" [Bauer 1980, pS88]. Lacking sufficient information, design engineers tend to apply tried-and-trusted elements rather than the latest technologies.

Although some research has been undertaken [Schmidt-Kretschmer 1994, Bruchhold 1988], much more research is needed into disassembly-supporting connections, in particular analytical and experimental research into strength and disassembly characteristics. We therefore undertook research to determine these characteristics in order to be able to provide designers with the necessary information and to extend the use of these connections. Some results of the experimental investigations are presented in this paper.

3. Connections and Fasteners

Within the scope of the research project it is not possible to analyse the entire range of connections that support disassembly for maintenance and recycling purposes. The investigations focused on connections that can be disassembled without destruction (for details see [Klett et al. 2002, p1]). Their working principles facilitate disassembly as well as assembly, i.e. they support recycling and maintenance as well as manufacturing. Disassembly-supporting connections facilitate the disassembly process by requiring only simple operations that involve fast and easy locking and unlocking using small forces or torques and small distances or angles [Schmidt-Kretschmer 1994, p18].

The experiments concentrated on quarter-turn fasteners. This type of connection is somewhat similar to bolted joints and has a great potential for a broader use, especially to substitute screws in some applications. Figure 1 shows three different types of quarter-turn fasteners.

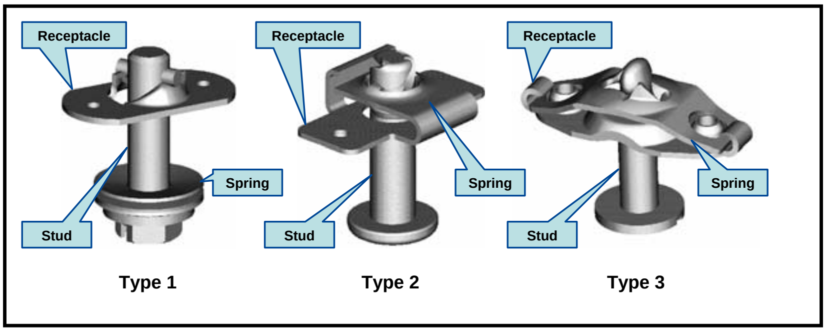

Figure 1. 3D-models of three different types of quarter-turn fasteners

All three types of fasteners have the same working principle, but their form is different. A quarter-turn fastener consists of a headed stud, a retaining ring (not shown) and a receptacle for engagement with the stud. An elastic element within the flowline of force is added to provide a specific preload and to allow for tolerances. This spring element can be integrated in the receptacle (type 2 and type 3) or included as a separate component (type 1). The locking and unlocking occurs by rotating the stud approximately 90 degrees. In doing so, a small pin runs along a double-sided guide until the pin engages at the end of the lead when locking. The lead can be integrated in the stud (type 2) or in the receptacle (type 1 and type 3) while the pin is situated at the counterpart.

To determine the strength characteristics of six different quarter-turn fasteners of the three types displayed in Figure 3, the following data were obtained from catalogues (see Table 1) [Wünsche 2006]:

$l_{K,un}$	Lower clamp length → Minimum total thickness of the components to be connected, as specified by manufacturer.
$l_{K,ob}$	Upper clamp length → Maximum total thickness of the components to be connected, as specified by manufacturer.
d_{VZ}	Stud diameter → Diameter of the stud, as specified by manufacturer.
F_{max}	Maximum load → Maximum force, as specified by manufacturer.
m	Mass → Mass of the fastener without retainer.

Table 1. Data of the chosen quarter-turn fasteners

Specimen	**$l_{K,un}$ [mm]**	**$l_{K,ob}$ [mm]**	**d_{VZ} [mm]**	**F_{max} [N]**	**Head**	**m [g]**
Type 1	19.95	20.70	9.5	10000	Slotted hexagon head with collar	45.5
Type 2	22.00	22.90	9.0	290	Slotted oval head	30.5
Type 3	14.50	15.00	5.0 (?)	2000	Slotted oval head	13.7
Type 4	19.55	20.55	10.0	--[1]	Slotted hexagon head with collar	57.9
Type 5	19.90	20.70	8.2 (?)	10000	Slotted hexagon head with collar	48.9
Type 6	19.90	20.70	9.4	10000	Slotted hexagon head with collar	48.0

The types 1 to 6 are from different manufacturers. Type 1 to 3 represent the three different types as shown in Figure 3 while type 4 to 6 are of the same type but of different shapes of the receptacle as type 1. The different shapes of these receptacles resulted mainly from different manufacturing technologies.

4. Strength Characteristics

The strength characteristics were determined using static and dynamic tension tests.

4.1 Static tension test

Aims: The static tension test serves to determine the strength of connections under axial static load at ambient temperature. This test is carried out to determine the following characteristics:

F_m	Maximum force → Force at tensile strength.
$F_{0.2}$	Force at proof strength.
$F_{F,max}$	Maximum spring force → Force of the spring element at solid length.
$F_{0.2,rel}$	Proof strength ratio → Quotient of force at proof strength and force at tensile strength.
f_m	Specific maximum force → Force at tensile strength relating to its mass.

The characteristics derived as a result from the test are arithmetic means of the characteristics determined at each available specimen.

Testing method: The static tension tests were executed according to EN 10002-1:2001 and ASTM E111:2004. Tension force and elongation were continuously measured and recorded. For every type ten specimens were used. The cross head speed was set to 5mm/min.

Testing machine: An universal testing instrument by Instron Ltd. was used to carry out the static tension test. This is a floor model machine with a cross head drive, which is operated by two vertical drive screws and a load cell that uses strain guages and has 2.5 kN maximum load capacity.

Results: Typical force-elongation curves of one specimen per chosen quarter-turn fastener type are shown in Figure 2. Table 2 summarises some results of the static tension test. All graphs feature a

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[1] There was no data available from the manufacturer.

characteristic gently inclined starting range caused by the spring element which passes into a distinctive material elastic range after the spring element reached the solid length. Type 1 has the largest maximum force, whilst type 2 shows the largest elongation. The maximum loads of all quarter-turn fasteners as specified by the manufacturers (see Table 1) differ significantly from the test results (see Table 2). For type 2 a maximum load is specified by the manufacturer which is clearly below the determined maximum force and the force at proof strength as well as below the determined maximum spring force. For type 1 the specification of the manufacturer lies far above the determined force at proof strength which is the most relevant parameter for dimensioning.

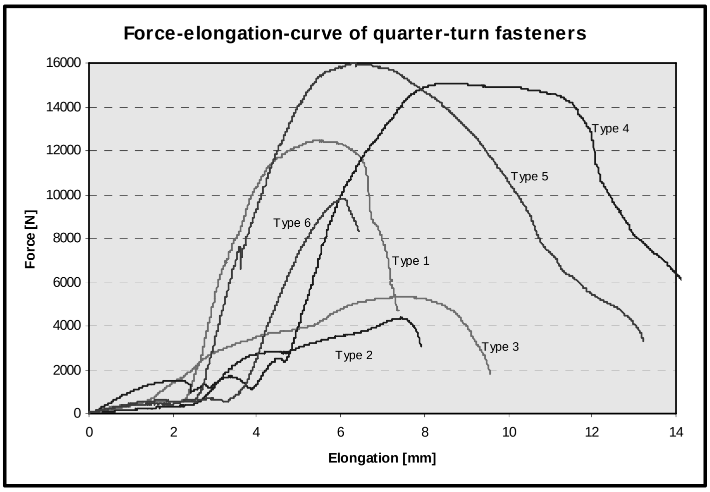

Figure 2. Typical force-elongation-curves for the chosen quarter-turn fasteners

To compare different fasteners regarding their behaviour against static load, it is useful to normalise the characteristics. In this case, the specific maximum force f_m (see equation (1)) was defined as maximum force per unit mass.

$$f_m = \frac{F_m}{m} \tag{1}$$

This parameter is the measure for the utilisation of the used material mass. The higher the specific maximum force is the better is the degree of mass utilisation. Type 2 has a poor mass utilisation (see Table 2) because the stud is too massive in comparison to the receptacle (see Figure 1). So, this type fails due to rupture of the receptacle. Due to the balanced proportion of mass, type 3 shows a good degree of utilisation.

Table 2. Results of the static tension test for the chosen quarter-turn fasteners

Specimen	F_m [N]	$F_{0.2}$ [N]	$F_{F,max}$ [N]	$F_{0.2,rel}$ [%]	f_m [N/g]	Failure
Type 1	12500	7330	600	59	275	Rupture of receptacle
Type 2	4220	2340	420	55	138	Rupture of receptacle
Type 3	5430	2890	720	53	395	Deformation of receptacle
Type 4	14500	8750	2760	60	250	Rupture of receptacle/stud
Type 5	15250	7870	620	52	312	Rupture of receptacle/stud
Type 6	9710	5750	800	59	202	Rupture of stud

Weak point of most of the tested quarter-turn fasteners regarding static load is the receptacle. Figure 3 shows some typical failure cases for the receptacles of type 1 to type 6. At type 1 breaks almost the whole double-sided guide at the receptacle while at type 4 only a small part at the contact area between stud and receptacle breaks. Type 5 fails through a disruption of the receptacle into several parts. In these cases an inadequate flowline of force inside the receptacle due to their shape is the reason for failure. At type 4 and type 5 the stud fails at the same time as the receptacle too. The main reason for failure of type 2 is the underdimensioning of the receptacle compared to the stud. The pins at the receptacle which join in the stud rupture. At type 3 the receptacle are so deformed that the stud is drawn through.

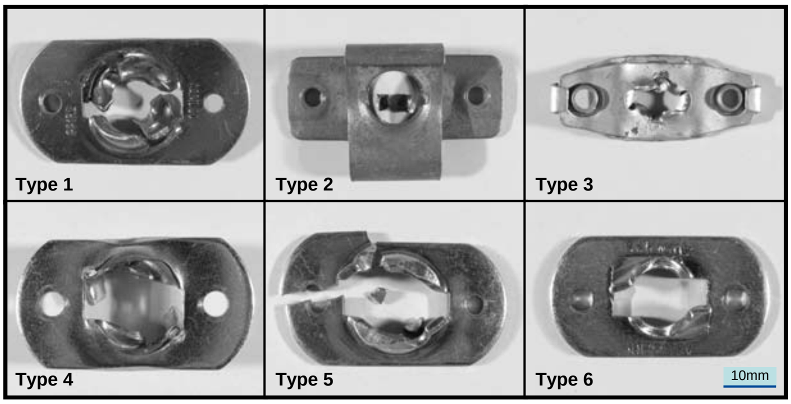

Figure 3. Typical failure cases of the receptacles regarding static load

Application: Maximum force and force at proof strength are necessary for designing. Knowledge about these characteristics is a fundamental prerequisite for the dimensioning of statically loaded components to avoid failure due to plastic deformation. They can be used to compare connections regarding their strength. The maximum force of the spring element allows conclusions about the permissible preload of the connection. On the basis of the failure analysis an optimisation of the connections regarding strength is possible.

4.2 Dynamic tension test

Aims: The dynamic tension test – or fatigue test – serves to determine the strength of connections under axial dynamic load at ambient temperature. This test is carried out to determine the following characteristics:

F_m	Mean force (for details see [Wünsche et al. 2005]).
$F_{D10\%}$	Force at endurance strength for a survival probability of 10%.
$F_{D50\%}$	Force at endurance strength for a survival probability of 50%.
$F_{D90\%}$	Force at endurance strength for a survival probability of 90%.
$F_{D50\%,rel}$	Endurance strength ratio → Quotient of force at endurance strength for a survival probability of 50% and force at proof strength.
$f_{D50\%}$	Specific force at endurance strength → Force at endurance strength for a survival probability of 50% relating to its mass.

The characteristics derived as a result from the test are arithmetic means of the characteristics determined at each available specimen.

Testing method: To determine fatigue strength various methods exists, depending on the test facility, the number of available specimen and the required accuracy of measurement. Due to the limited number of specimens used in this test, the *modified staircase method*[2] was chosen. This is a time- and

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[2] This method was originally developed by Dixon & Mood (1948) and later modified by Hück (1980). It is also known as Up-and-Down-Method.

cost-saving method for the experimental assessment of the fatigue strength for a survival probability of 50% taking the mean, the scatter and the confidence limits into account [Hück 1983, p406].

For the dynamic tension tests 27 specimen of each type were available. To achieve useful data for mean and standard deviation 17 specimens were used to obtain valid tests. The other specimens were used to find out the transition range starting from the first load level (for details about the testing method see [Wünsche et al. 2005]).

The tests were carried out with a frequency of 100 Hz. After 10^7 load cycles the tests were abandoned and the unbroken specimen assessed as "non-failure".

Testing machine: To carry out the dynamic tension test a Hydropuls servo-hydraulic testing machine (Carl Schenck AG) was used.

Results: Table 3 summarises some results of the dynamic tension test. Some of the tested quarter-turn fasteners show a relatively low force at endurance strength compared to the determined force at proof strength like type 1 and type 2. Other quarter-turn fastener have a force at endurance strength which utilise almost the whole force at proof strength like type 4 and type 6 (see Table 3).

To compare different fasteners regarding their behaviour against dynamic load, it is useful to normalise the characteristics. In this case, the specific force at endurance strength $f_{D50\%}$ (see equation (2)) was defined as force at endurance strength per unit mass.

$$f_{D50\%} = \frac{F_{D50\%}}{m} \tag{2}$$

This parameter is the measure for the utilisation of used material mass. The higher the specific force at endurance strength is the better is the degree of mass utilisation. Due to the misproportion of the stud in comparison to the receptacle type 2 has a poor mass utilisation (see Table 3).

Table 3. Results of the dynamic tension test for the chosen quarter-turn fastener

Specimen	F_m [N]	$F_{D10\%}$ [N]	$F_{D50\%}$ [N]	$F_{D90\%}$ [N]	$F_{D50\%,rel}$ [%]	$f_{D50\%}$ [N/g]	Failure
Type 1	4000	4620	4800	4395	65	79	Rupture of receptacle
Type 2	1400	1725	1220	1550	69	53	Rupture of receptacle
Type 3	1800	2510	2300	2155	79	167	Rupture of receptacle
Type 4	5800	8660	8200	7815	94	142	Rupture of receptacle
Type 5	4200	8900	5910	4820	75	121	Rupture of receptacle/stud
Type 6	3300	9815	4715	3605	82	98	Rupture of stud

Weak point of most of the analysed quarter-turn fasteners regarding dynamic load is also the receptacle. Figure 4 shows some typical failure cases for the receptacles of type 1 to type 6. At type 1 and type 5 the receptacle typically breaks at the contact area of stud and receptacle because of poor force transmission. The shape of these receptacles at the point of force transmission is contrary to the principle of direct and short force transmission, which means, that "the shortest and most direct force transmission path is the best" [Pahl & Beitz 1996, p240]. Due to its shape the receptacle underlies shearing stress at this position instead of compressive stress. Type 4 and type 6 have a better shape concerning this design principle. So these types fail typically due breaks at either the stud itself or the small pin across the stud. In case of type 2 and type 3 the receptacle breaks in the region of the spring element. But these fasteners have a certain fail-safe property because after rupture of the spring element the remaining part of the receptacle prevents the separation of the connection.

Application: Force at endurance strength is also necessary for designing. This characteristic is a fundamental prerequisite for the dimensioning of dynamic stressed components to avoid failures due to fatigue. On the basis of the results of this test conclusions about the long-term behaviour under changing stress are possible. The results of the failure analysis can be used to identify potentials for optimisation of these connections regarding strength.

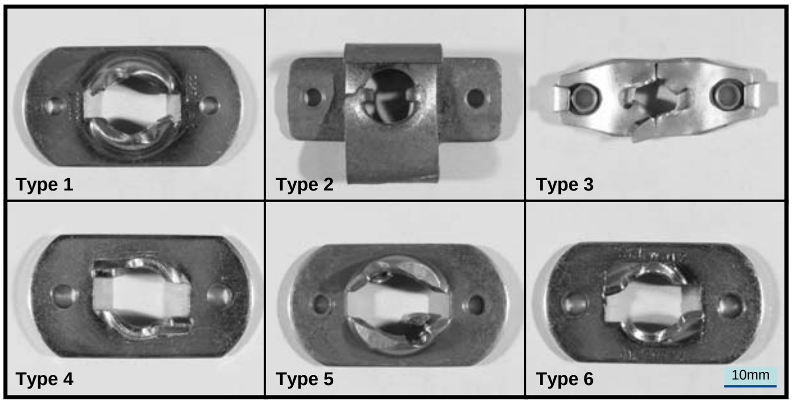

Figure 4. Typical failure cases of the receptacles regarding dynamic load

5. Discussion of results

Figure 5 shows a comparison of the utilisation of the material of the analysed types of quarter-turn-fasteners at static and dynamic load. The proof strength ration is a quotient of the force at proof strength $F_{0.2}$ and the maximum force F_m. This ratio characterises the utilisation of the material at static load. The endurance strength ratio is a quotient of the force at endurance strength $F_{D50\%}$ and the force at proof strength $F_{0.2}$. This ratio characterises the utilisation of the material at dynamic load. The position within this rating diagram allows conclusions about the design regarding static and dynamic load. The higher a type is placed in this diagram the better is the design regarding dynamic load. The mor right it is placed the better it is designed concerning static load. So, type 4 and type 6 have a good design regarding dynamic load, because they utilise the force at proof strength very good. But all types doesn't show a good utilisation of the maximum force.

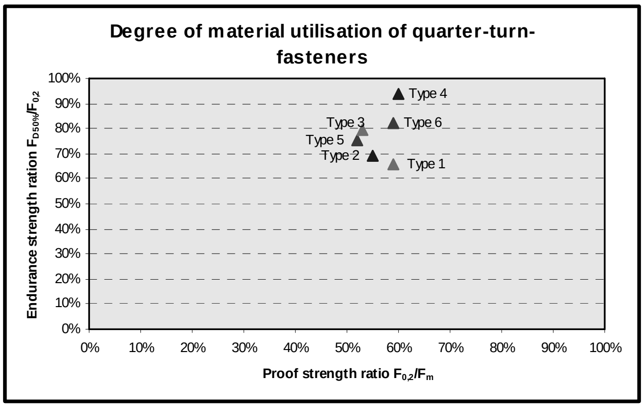

Figure 5. Rating diagram for utilisation of material strength of quarter-turn-fasteners

Based on the analysis of the damage causes some potentials for the optimisation of material and shape can be derived. The strength of most of the tested quarter-turn fasteners can be increased if the *principle of uniform strength* and the *principle of direct and short force transmission* are considered. The carefully selection of material and shape having regard to the first design principle ensures "that each component is of uniform strength and contributes equally to the overall strength" while the consideration of the second design principle ensures a "minimum volume, weight and deformation and … should be applied particular if a rigid component is needed" [Pahl & Beitz 1996, p248]. A good example for a fastener with uniform strength is type 5 because receptacle and stud fail mostly at the same time. The receptacle of type 6 is a good example for a shape with a direct force transmission path. Through the avoidance of sharp notches within the flowlines of force – especially at the receptacles – the strength against dynamic load can further increased. So, sharp edges at the recess of the receptacle should be avoided because these edges are the starting point for cracks which leads to failure.

6. Conclusion

The characteristic values and diagrams ascertained through the strength analysis is meant to support the selection of connections and fasteners. With the information gathered with the described tests, the present selection based on qualitative information and experience can be enriched by quantitative parameters to make the selection safer and more reliable. The chosen parameters help to describe the state-of-the-art regarding disassembly-supporting connections.

The main criteria for the selection of connections apart from their geometry are load carrying capacities for static as well as dynamic loads and the associated preload forces. With the knowledge about damage causes, it was possible to point out potentials for optimisation of design and geometry.

The aim of this project is to develop a knowledge base which can support the design engineer with the selection of disassembly-supporting connections. The collected information about the properties of existing disassembly-supporting connections should form a basis for standardisation. In addition the analysis should support the application of disassembly-supporting connections to a broader extent. The tests could clarify that disassembly-supporting fasteners and connections can be used under higher loads than currently applied and that they represent a competitive alternative to conventional connecting elements.

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