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ANALYSIS OF CONNECTIONS AND FASTENERS TO DETERMINE DISASSEMBLY AND STRENGTH CHARACTERISTICS

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1 Introduction

The increasing number of product functions and maintenance requirements as well as the necessity of cheaper production puts large demands on the product structure, i.e. the layout of the product components and of their connections. As a consequence, the number of requirements increases causing an increasingly more difficult to manage number of conflicting aims. This is particularly true for maintenance and recycling requirements. These requirements have become more and more important due to changed product strategies, other concepts of use or legislative measures. The disassembly of technical products as a decisive part of maintenance and recycling are substantially affected by the connections within the product, the product structure and the design of the connected components. Warranty and product liability are further requirements whose impact on designing technical products increased enormously due to increased legislation concerning consumer rights.

For designing optimal products it is necessary to choose the right connections, because the connection technology exceedingly influences the economy of manufacture, maintenance and recycling 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" [1, p1].

The paper focuses on a detailed description of the aims and the methods of the tests, which were used to analyse the considered connections. This paper doesn't focus on the interpretation of the testing results. Using three connections of the same type but different embodiments the approach to determine the defined and specified characteristics are exemplified.

2 Aims and Objectives

"Connections are an essential part of engineering. The technology begins primarily with the connecting." [2, pS82] Without connections there are no functional and efficient technical systems. Complex products are made of single parts, which can fulfil their assigned tasks only when they are connected. For connections to be efficient, reliable, safe and economic requires their design to be oriented towards these goals. The working loads, the resulted stresses as well as general, boundary and environmental conditions that are determined in the early stages of the product development process provide the required information for selecting and designing 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." [3, p85]

To meet all the different requirements and the many – partly contrary – design aims, the design engineer needs sufficient knowledge about the characteristic features and peculiarities of connections. This knowledge is hardly available 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 make the access and [thus] the (universal) application in the design process difficult" [4, p2]. The only available information about disassembly-supporting connections can be found in supplier brochures, catalogues and technical literature. The information given is mostly limited to geometric data whilst details concerning strength, assembly and disassembly are almost completely absent. Furthermore, these publications are hard to find and usually not very easy to use. As a result of a comprehensive investigation of German standards and guidelines we found that no real standardisation exists, although "there are 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" [2, pS88]. Lacking sufficient information, design engineers tend to apply well-known elements rather than the latest technologies.

This leads us to the assumption that "Disassembly-supporting connections are not used in practice because the connections and their properties are not known." To check this assumption, we carried out a postal survey using questionnaires within German manufacturing industry. The main aims were to investigate how well disassembly-supporting connections are known and used, and what the reasons are for designers not to use these connections (for further details see [5]). The survey confirmed our assumption. Most of the investigated disassembly-supporting connections are not well-known and hardly used. Figure 1 shows the reasons the respondents (n=196, multiple answers possible) stated for not considering these connections.

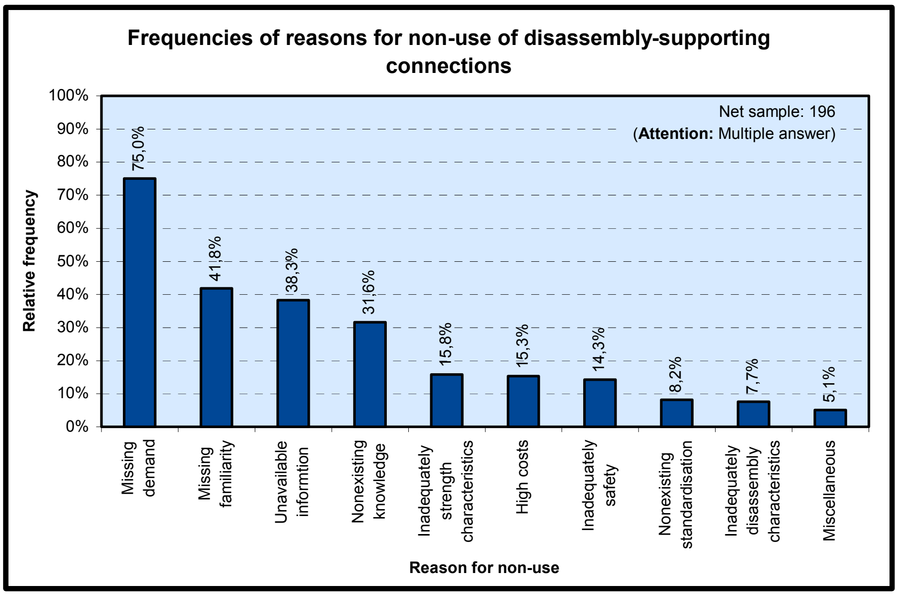

Figure 1. Reasons for non-consideration of disassembly-supporting connections

Three out of four respondents stated that they see no demand for their application. More than a third is not able to use these connections because they are not familiar with these types of connections. Nearly the same proportion stated that there is no information available about these connections. Information in this context is defined as data about the properties and characteristics of the considered connections. A third of the respondent states a lack of experience with handling these connections and their application to particular technical products (in Figure 1 referred to as “Nonexisting knowledge”). Further reasons are inadequate properties, doubts about product safety and uncertainty about the application of these connections, e.g. because standardisation is lacking.

Figure 2 shows that more than three quarter of the respondents use assembly and disassembly criteria – besides the usual stress, geometry and functional criteria – to select a connection. It was also found that assembly and disassembly is considered very important for selecting connections to more than two third of the respondents. Only a quarter of the respondents stated that they use recycling as criterion. An analysis of the link between the use of criteria and the importance every respondent attaches to a particular requirement shows that more than half of all respondents attach a certain level of importance to recycling even if only less than a half of them use it for selection.

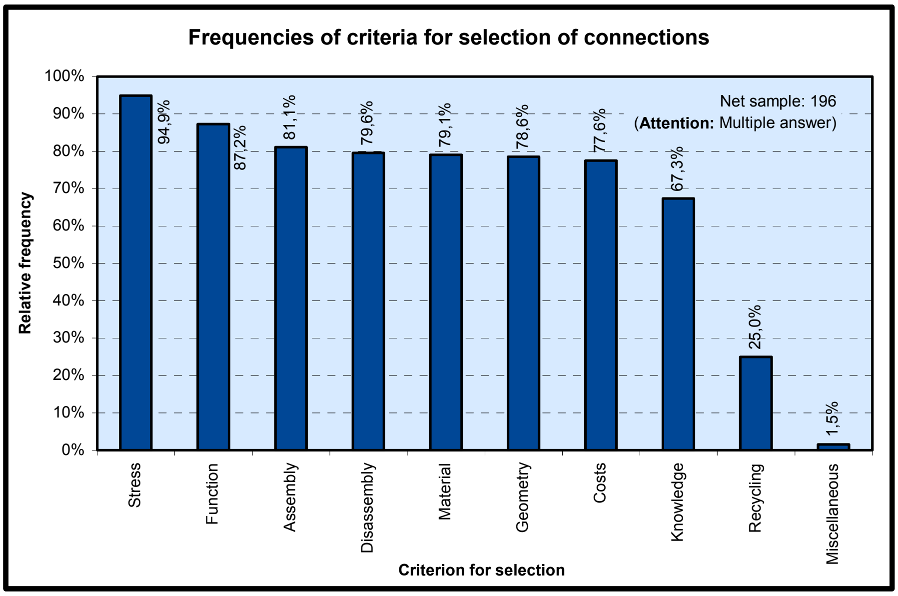

Figure 2. Criteria for the selection of connections

Although some research has been undertaken [4, 6], the survey showed that far more research into disassembly-supporting connections is needed, 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. The 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 variety of connections that support disassembly as a part of the recycling process and as a part of maintenance. The investigations focused on connections that can be disassembled without destruction (for details see [7, 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 [4, p18]. They can be classified according to the design of the connecting zone, i.e. how each component is arranged and connected within the connection. This results in four connection modes that can be used for the selection of suitable connections (for examples see Table 4, for details see [7, p3]).

A *penetrating connection* mode means that the fastener will go through the component(s), i.e. the component(s) require a hole. A *coupling connection* mode means that the components are connected by a fastener which is positioned between the components, i.e. the fastener has to be connected with the component too. An *entangling connection* mode means that the fastener will span the component, i.e. the fastener surrounds the components. An *integrated connection* mode means that the feature for connecting is included in the component.

The experiments are 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 3 shows three different types of quarter-turn fasteners.

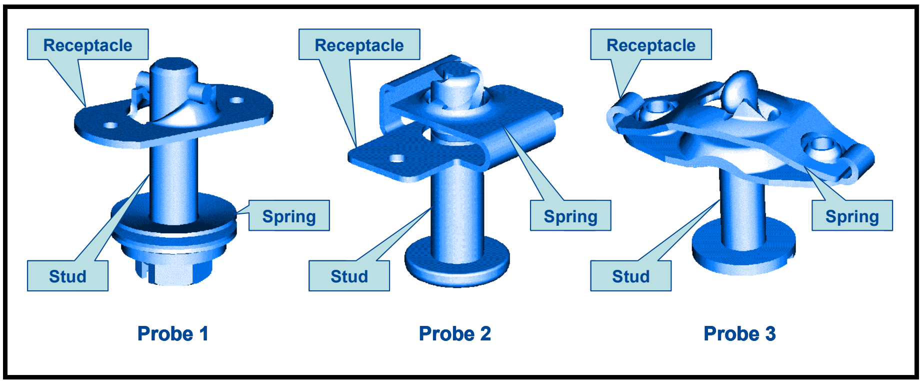

Figure 3. 3D-models of three different types of quarter-turn fasteners

All three types of fastener have the same working principle, but their embodiment is different. A quarter-turn fastener consists of a headed stud, a retaining ring (not displayed) and a receptacle for engagement with the stud. Within the force flow an elastic element is added to provide a specific preload and to compensate for tolerances. This spring element can be integrated in the receptacle (probe 2 and probe 3) or included as a separate part (probe 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 (probe 2) or in the receptacle (probe 1 and probe 3) while the pin is situated at the counterpart.

To determine the strength and disassembly characteristics of the three types of quarter-turn fasteners displayed in Figure 3, the following data was obtained from catalogues (see Table 1) [8, p49 et seqq.; 9, p43 et seqq.; 10, p269 et seqq.]:

$l_{K,un}$	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]**
Probe 1	19.95	20.70	9.5	10000	Slotted hexagon head	45.5
Probe 2	22.00	22.90	9.0	290	Slotted oval head	30.5
Probe 3	14.50	15.00	5.0	2000	Slotted oval head	13.7

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 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.

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

Testing machine: To carry out the static tension test a Universal testing instrument by Instron Ltd. was used. 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 gages and has 2.5kN maximum load capacity.

Results: The force-elongation curves of the chosen quarter-turn fasteners are shown in Figure 4 whilst Table 2 summarises the main results of the static tension test. All graphs feature a characteristic gently inclined starting range caused by the spring element which pass into a distinctive material elastic range after the spring element reached the solid length. Probe 1 has the largest maximum force, whilst probe 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 probe 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 probe 1 the specification of the manufacturer lies far above the determined force at proof strength which is the most relevant parameter for dimensioning.

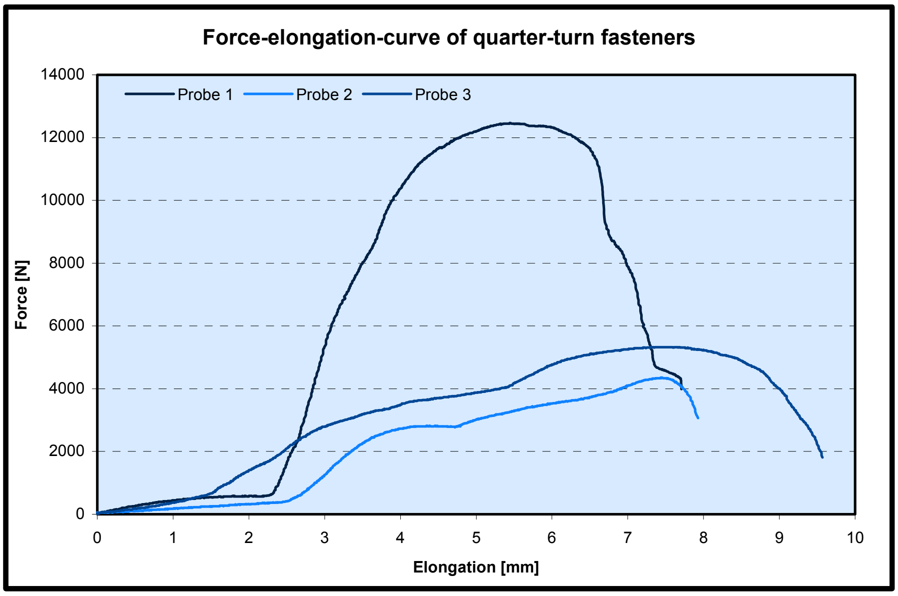

Figure 4. Force-elongation diagram for the tension test

To compare the characteristics of different fasteners, 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 material. The higher the specific maximum force is the better is the utilisation of material. Probe 2 has a poor utilisation of material (see Table 2) because the stud is in comparison to the receptacle too massively (see Figure 3). Caused by the balanced proportion of mass, probe 3 shows a good degree of utilisation.

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

Specimen	**F_m [N]**	**$F_{0.2}$ [N]**	**$F_{F,max}$ [N]**	**$F_{0.2,rel}$ [%]**	**f_m [N/g]**	**Failure**
Probe 1	12500	7330	600	59	275	Rupture of receptacle
Probe 2	4220	2340	420	55	138	Rupture of receptacle
Probe 3	5430	2890	720	53	395	Deformation of receptacle

The weak point of all tested quarter-turn fasteners regarding static load is the receptacle. Underdimensioning of the receptacle – compared to the studs – and an inadequate force flow inside the receptacle are the main reasons for it.

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:

$F_{D10\%}$ 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%.

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 specimen used in this test, the *modified staircase method*[1] was chosen. This is a time- and 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 [11, p406].

The test scheme consists of a number of linked tests. A specimens is loaded with a constant amplitude until a predefined number of load cycles ($N=10^7$) is reached. Then the test is stopped. If the specimen breaks before this maximum number of load cycles is reached, the next specimen is loaded at a lower load level. Otherwise the next specimen is loaded at a higher level. The size of the steps between the load levels is defined prior to the test series. The first load level is taken at a level above the expected fatigue strength.

Using the modified staircase method, all occurrences – "failures" and "non-failures" – are taken into account in the evaluation of the results. The first specimens of each test series are used to find out the appropriate load level (see Figure 5). Of these specimens only those are included in the analysis, that are confirmed by at least one test at the same load level. The result of the last specimen of a series contains the information of the following load level. Therefore an additional, virtual test can be included in the evaluation of a test series. Figure 5 shows the procedure for the evaluation of a sequence of tests. The result is the mean of the fatigue strength, which complies with the endurance strength for a survival probability of 50% (see equation (2)) [11, p410].

$$F_{A50\%} = F_{A0} + \left(d \cdot \frac{A}{F} \right) \tag{2}$$

Considering the standard deviation and standard error and the chosen confidence level allows the endurance strength for other survival probabilities to be determined. For this at least 17 tests are necessary to have useful data for the required standard deviation.

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

1	2																							3	4	5	6
F_a [N]	**x** Failure, **o** Non-failure, **+** Virtual test, **( )** Invalid test																							i	f	i*f	i²*f
3400	**(x)**																										
3000		**(x)**																									
2600			**(x)**																								
2200				**(x)**																							
1800					**(x)**																						
1400						**x**										**x**								3	2	6	18
1000							**x**				**x**		**x**		**o**		**x**				**x**		**+**	2	6	12	24
600								**x**		**o**		**o**		**o**				**x**		**o**		**o**		1	7	7	7
200									**o**										**o**					0	2	0	0
0																											
																									17	25	49
																									F	A	B

Figure 5. Test and evaluation scheme of the modified staircase method (exemplary for probe 1)

To determine mean force, force amplitude and progressive ratio, the results of the tension tests were used. First the maximum and minimum forces were defined. The force at proof strength $F_{0.2}$ was chosen as maximum force, because the focus was on elastic behaviour. The maximum force $F_{F,max}$ the spring element can apply (i.e. maximum preload) was chosen as minimum force because the fastener itself and not the spring element should be tested. After that the mean force F_m (see equation (3)) and the force amplitude F_a (see equation (4)) for the first load level could be determined.

$$F_m = \frac{\left(F_{0,2} + F_{F,\max}\right)}{2} \tag{3}$$

$$F_a = \frac{\left(F_{0,2} - F_{F,\max}\right)}{2} \tag{4}$$

For the dynamic tension tests 27 specimen of each connection 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. The optimal progressive ratio is dependent on the planned number of tests and an expected standard deviation. With 17 valid tests the ratio of expected standard deviation and progressive ratio should amount 0.7 [11, p414]. The Standard deviation was assumed with 8% of the force amplitude. So the progressive ratio d (see equation (5)) could be determined.

$$d = \frac{s}{0.7} \cdot \frac{\left(F_{0,2} - F_{F,\max}\right)}{2} \tag{5}$$

The tests were carried out with a frequency of 100Hz. After reaching the ultimate numbers of load cycles amounting to 10^7 cycles the tests were abandoned and the unbroken specimen assessed as “non-failure”.

Testing machine: To carry out the dynamic tension test a Hydropuls-system by Carl Schenck AG was used which is a servo-hydraulic testing machine.

Results: Table 3 summarises some results of the dynamic tension test. The first value for the progressive ratio d in this table represents the determined value according to equation (5). Because this value was too large to get an analysable sequence of stairs (i.e. adequate number of valid tests), the second value was chosen. All of the tested quarter-turn fasteners show a relative low force at endurance strength compared to the determined force at proof strength. The weak point of all these fasteners regarding dynamic load is also the receptacle. In two cases (probe 2 and probe 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 remained part of the receptacle prevents the separating of the connection. At probe 1 the receptacle mostly breaks starting from the contact area of stud and receptacle because of poor circumstances of force transmission.

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

Specimen	F_m [N]	F_a [N]	d [N]	$F_{A10\%}$ [N]	$F_{A50\%}$ [N]	$F_{A90\%}$ [N]	Failure
Probe 1	4000	3400	400	1620	800	395	Rupture of receptacle
Probe 2	1400	1000	100/50	325	220	150	Rupture of receptacle
Probe 3	1800	1100	100/50	710	500	355	Rupture of receptacle

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.

5 Disassembly Characteristics

The experimental analysis focuses on the determination of disassembly characteristics by means of quasi-static and dynamic locking-unlocking tests as well as tests to determine disassembly time.

5.1 Static locking-unlocking test

Aims: The static locking-unlocking test serves the determination of the assembly and disassembly behaviour of connections at one locking-unlocking process. With this tests the occurring forces or torques, as well as the occurring displacements or angles are continuously recorded. For non-positive connections the preload forces and displacements can be determined. This test is carried out to determine the following characteristic:

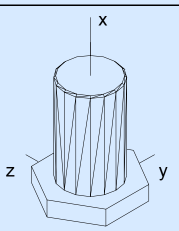
M_F	Locking torque → Torque at the locking process of the connection.
φ_F	Locking angle → Angle at the locking process of the connection.
η_F	Locking efficiency → Quotient of energy accumulated in the connection and work done while locking the connection.
M_L	Unlocking torque → Torque at the unlocking process of the connection.
φ_L	Unlocking angle → Angle at the unlocking process of the connection.
η_L	Unlocking efficiency → Quotient of energy accumulated in the connection and the sum of accumulated energy and work done while unlocking the connection.
F_V	Preload force → Force of the locked connection caused by the springy element.
s_V	Preload displacement → Displacement of the locked connection caused by the springy element.
S_V	Preload coefficient → Quotient of the preload force and the maximum preload force at the locking-unlocking process.

Testing method: A complete static locking-unlocking test for one connection consists of six main stages: Pre-processing, unloading, loading, unlocking, locking and post-processing. All these stages are executed only once. The stage *pre-processing* contains the establishing of the initial situation of the testing machine, the mounting of the specimen and the adjustment of the required clamp length. So the starting position is a locked connection. In this stage no data are recorded. In the stage *unloading* the connection is unloaded until the preload force is completely exhausted while preload force and preload displacement are continuously measured. In the stage *loading* the connection is loaded again until the previous preload force is reached while preload force and preload displacement are measured too. The data collected in these two stages are used to determine the energy accumulated in the connection. In the stage *unlocking* the connection is changed into opened condition while preload force, unlocking force and unlocking angle are continuously measured. In the stage *locking* the connection is changed into closed condition while preload force, locking force and locking angle are measured. The data collected in these two stages are used to determine the efficiencies of the connection. The stage *post-processing* contains the recording and saving of the data and the re-establishing of the initial situation of the testing machine.

For every connection type ten specimens were used. The locking-unlocking speed was set to 2.0rpm while the loading-unloading speed was set to 2.0mm/min.

Testing machine: To carry out the locking-unlocking tests, a special testing machine is needed, which is able to test these connections and fasteners with all these different locking-unlocking kinematics.

Table 4. Analysis of the assembly and the disassembly motions of disassembly-supporting connections

Connections and fasteners		Assembly			Disassembly	
 R → Rotation, T → Translation		Primary motion of locking	Secundary motion of locking	Direction of preload	Primary motion of unlocking	Secundary motion of unlocking
Penetrating connections	Push-turn fasteners	T_x		T_x	R_x	T_x
	Pull-push fasteners	T_x		T_x	T_x	
	Circular wedge connections	(T_x), R_x			R_x, (T_x)	
	Bolted joints	R_x	T_x	T_x	R_x	T_x
	Quarter-turn fasteners	(T_x), R_x	T_x	T_x	R_x	T_x
Entangling connections	Hose clips	R_y	T_y	T_y, T_z	R_y	T_y
	Toggle latches	T_y	R_z	T_x	T_y	R_z
Coupling connections	Push-push fasteners	T_x		T_x	T_x	
	Clamp connections	R_x	T_x	T_x	R_x	T_x
Integrated connections	Bayonet joints	(T_x), R_x		T_x	R_x, (T_x)	
	Snap joints	T_x	T_y	T_x	T_x	T_y

For the previous tests [4, 6] small and simple testing machines were used, which were very inflexible because tailored to a special connection type with definite sizes. For every connection type another testing machine were needed. This procedure was very expensive and needs a lot of space and equipment. Furthermore the data obtained with these machines were comparable with each other only with care. Thus a new universal applicable testing machine was developed and built, which is now able to test most of the considered disassembly-supporting connections and some further connections.

First connections with strong differing locking-unlocking kinematics had to found out. Table 4 gives an overview of the kinematics analysis, which shows that the entangling connections regarding consistency of preload and locking-unlocking direction strongly differs from the others. The complexity of this locking-unlocking kinematics leaded to their non-consideration for the development of the universal testing machine. The realisation of assembly and disassembly motions of the other connections seemed to be realistic.

Starting from previous work [4, 6] and from kinematics analysis as well as from device-related and infra-structural conditions the requirements of a universal applicable testing machine were acquired. Then a few principle solutions were systematically worked out according to the methodological approach [12]. Taking economic and technical circumstances, guidelines for design for ease of disassembly as well as collected knowledge about connections into account the final concept – selected due to its simple, compact and modular structure – was detailed and finalised.

Finally the realisation of the definitive layout of the testing machine and the setup of the controlling devices were realised in the workshop of our subject area. Figure 6 shows the realised testing machines, which is characterised by a modular structure, a low assembly depth, the especially use of standard parts und the application of predominantly detachable connections with uniform embodiments.

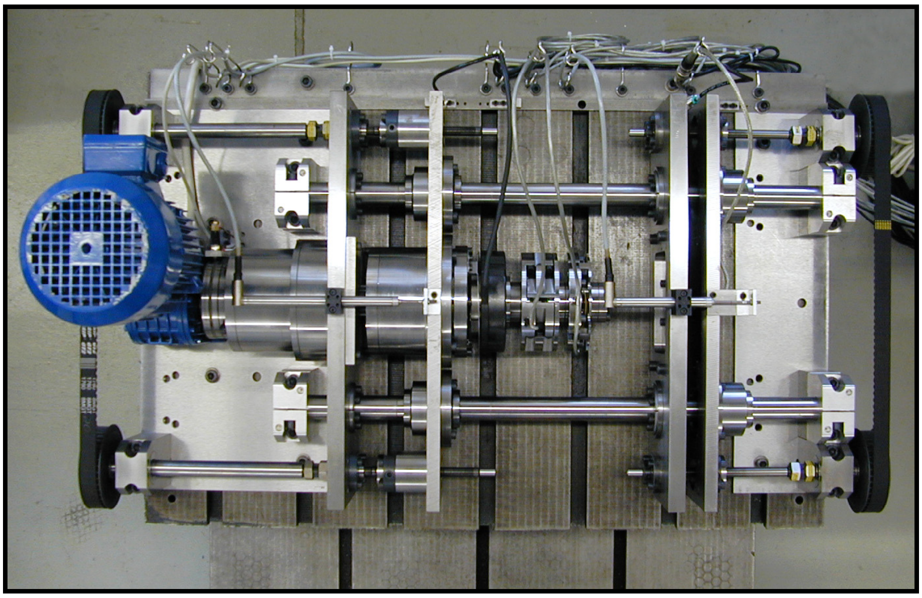


Figure 6. Testing machine for determining disassembly characteristics

The testing machine consists of two parallel guiding rods on which two pairs of slabs are arranged. One pair of slabs is responsible for holding and moving the tool, whilst the other pair provides the retaining of specimens. In each case one of the slabs is fixed at the guiding rods. The each corresponding slabs are arranged moveably along the guiding rods. Every translatory moveable slab disposes of an own drive consisting of a worm gear motor, a cogged-belt drive and two threaded spindle drives. The tool has an additional rotatory drive.

Thus all motion combinations of penetrating, coupling and integrated connections can be realised. At the tool side there are four sensors to record the needed data. In each case one sensor measures the locking-unlocking forces and its corresponding displacements as well as the locking-unlocking torques and its corresponding angles. At the specimens side there are two sensors to determine the data. One sensor measures the preload forces and one sensor its corresponding preload displacements. The control of the testing machine and the monitoring and the acquisition of the data happen via PC by means of an intelligent modular PC-based measurement device and a self-written program.

Results: Table 5 summarises the main results of the static locking-unlocking test. Probe 1 show the highest locking and unlocking torques because of the high stiffness of the disc springs (see Figure 3) and the steep slope of the double-sided guide. In this case the unlocking torque is higher than the locking torque because the slope of the guide to be overcome during unlocking is steeper than the slope to be overcome during locking. The determined locking-unlocking angles are dependent on the size of the quarter-turn fastener. The determination of these parameters was very difficult because all the tested fasteners have a clear position in closed condition but an unclear position in opened condition.

Table 5. Results of the static locking-unlocking test for the chosen quarter-turn fastener

Specimen	M_F [Nm]	φ_F [°]	η_F	M_L [Nm]	φ_L [°]	η_L	F_V [N]	s_V [mm]	S_V
Probe 1	2.72	108	0.22	4.13	111	0.27	398	3.2	0.76
Probe 2	2.15	105	0.04	1.87	105	0.06	149	2.9	0.79
Probe 3	0.71	88	0.14	0.53	90	0.16	160	1.0	0.72

Application: The simplest and stand to reason possibility to use the determined characteristics is the direct utilisation at the selection of connections. A further possibility of utilisation is the comparison of several sizes and different types of connections using the derived efficiencies. Besides on the basis of the determined data an analysis and an optimisation of the working geometries are possible.

5.2 Dynamic locking-unlocking test

Aims: The dynamic locking-unlocking test serves the determination of the assembly and disassembly behaviour of connections at repeated locking-unlocking process. With this test the occurring maximum forces or torques over 1000 locking-unlocking cycles are recorded. This test is carried out to determine the following characteristic:

- $M_{F,max}(n)$ Maximum locking torque at n locking-unlocking cycles
- $S_{F,dyn}(n)$ Dynamic locking coefficient at n locking-unlocking cycles → Quotient of maximum locking torque at n locking-unlocking cycles and maximum locking torque at first cycle.
- $M_{L,max}(n)$ Maximum unlocking torque at n locking-unlocking cycles.
- $S_{L,dyn}(n)$ Dynamic unlocking coefficient at n locking-unlocking cycles → Quotient of maximum unlocking torque at n locking-unlocking cycles and maximum unlocking torque at first cycle.
- $F_V(n)$ Preload force at n locking-unlocking cycles.
- $S_{V,dyn}(n)$ Dynamic preload coefficient at n locking-unlocking cycles → Quotient of preload force at n locking-unlocking cycles and preload force at first cycle.

Testing method: A complete dynamic locking-unlocking test for one connection consists of four main stages: Pre-processing, unlocking, locking and post-processing. The stages *unlocking* and *locking* are executed 1000 times. The stages *pre-processing* and *post-processing* are the same as at the static locking-unlocking test. In the stage *unlocking* the connection is changed into opened condition while only the maxima of preload force and unlocking force of each cycle are measured. In the stage *locking* the connection is changed into closed condition while only the maxima of preload force and locking force of each cycle are measured. For every connection type ten specimens were used. The locking-unlocking speed was set to 2.0rpm.

Testing machine: To realise these tests the same testing machine as used for static locking-unlocking tests is used.

Results: Due to the still ongoing tests on completion this paper no results can provided here. Thus please refer to the presentation or contact the author.

Application: By means of the determined data conclusions about the economic life-time and operational reliability are possible. Also the efficiencies derived from these tests can used to compare different types of connections.

5.3 Disassembly test

Aims: The disassembly test serves the determination of the behaviour of connections at the manual assembly and disassembly. With this test the times for connecting and locking and for unlocking and disconnecting respectively are measured. This test is carried out to determine the following characteristic:

t_M	Connecting time → Time for establishing the connection by joining and locking.
t_F	Locking time → Time for establishing the connection by simply locking.
t_L	Unlocking time → Time for undoing the connection by simply unlocking.
t_D	Disconnecting time → Time for undoing the connection by unlocking and unfastening.

Testing method: A complete disassembly test for one connection consists of four stages: Connecting, unlocking, locking and disconnecting. In the context of connections *connecting* is to join fastener and components and to lock the connection while *disconnecting* is to unlock the connecting and unfasten fastener and components. *Joining* is defined as the process to bring together fastener and components, while *locking* is the process to change the connection into closed condition. *Unfastening* is defined as the process to separate fastener and components while *unlocking* is the process to change the connecting into opened condition. Every connection was manual tested by ten test persons. The time measuring for every test stage starts with the grabbing and ends with the depositing of the tool(s), which seems to be suitable to the test person. After finishing a test stage the test persons were to be asked to rate the severity of the operation. The time, the used tool(s) and the severity for every test stage were recorded.

Testing machine: To carry out the disassembly test a special apparatus was build to simulate the connecting zone. This apparatus carries the retainers for the specimens, which represent the installation conditions specified by the manufacturer. To actuate the connections only standard tools like screwdrivers and spanners were used.

Results: Table 6 provides an overview of the main results of the disassembly test. The data show that customary quarter-turn fastener at the complete primary assembly require an extensive effort, which is caused by the design of the receptacle and in some cases by unsuitable installation data. The receptacles of these specimens are of such a design that they have to fix at one of the components to be connected by means of screwing, riveting, welding or bonding. This one-off additional effort is relativised by the benefit, which can be capitalised on the low locking-unlocking effort at repeated use e.g. during maintenance or recycling. "Only the total costs of the ready for use connection for the estimated total time of use of the machine or equipment can be a criterion for an economic evaluation of a connection" [3, p87]. Due to its self centring design (see Figure 3) probe 2 has some advantages during assembly. To establish a connection with the other specimen it is necessary to bring the stud in a defined position to the receptacle.

Table 6. Results of the disassembly test for the chosen quarter-turn fastener

Specimen	t_M [s]	t_L [s]	t_F [s]	t_D [s]	**Tools**
Probe 1	37.7	4.7	5.9	18.5	Screwdriver or ring spanner
Probe 2	34.9	5.1	4.9	18.1	Screwdriver
Probe 3	42.0	5.8	6.3	16.4	Screwdriver

Application: The determined data can be used for evaluation of the ease of maintenance and recycling of technical products. These data are also required for planning, evaluation and comparison of assembly and disassembly processes. A comparison of technical products regarding assembly and disassembly efforts may be another application area.

6 Conclusion

The characteristic values and diagrams ascertained through the mentioned disassembly and strength analysis is meant to support the selection of connections and fasteners. With the information gathered in this project, 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 next to their geometry are load carrying capacities for static as well as dynamic loads and the associated preload forces. With the knowledge about damage causes and locking and unlocking behaviour, it was possible to point out potentials for optimization of design and geometry. The locking-unlocking forces and torques determined through the disassembly analysis can be used to develop assembly and disassembly tools. Considering information about locking and unlocking distances and angles they allow the calculation of locking and unlocking work and efficiency. These parameters allow the comparison of different design or principle variants.

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 standardization. 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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