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Designing connections considering connecting and disconnecting process characteristics and the number of required fasteners

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1 Introduction

As products are mostly made up of separate components, connections are required to keep them together. *Connections* are defined as the areas where movements between components are restricted. Connections can be realised using features of the connected components themselves (e.g. a snap fit) or by using one or more additional components (e.g. a bolt and a nut), which we define here as *fasteners*. Connections are crucial for product quality because a poor connection can cause malfunction [1]. Specific connections also require specific connecting and disconnecting processes and determine the total number of parts. Connections are not only relevant for product quality but also for the assembly and disassembly process and they therefore contribute strongly to product benefits and costs. It can be concluded that determining the most suitable connections for a particular product is a crucial task.

This however is not an obvious task; the restriction of movements can be performed by a wide range of different connections with different fasteners and (dis-) connecting processes. The surveys of Schlüter [2] and Wünsche [3] suggest that the determination of connections is in many cases not traceable.

In the literature, many approaches for the dimensioning of specific connections, e.g. snap fasteners [2], [4], bolt nut connections [1] etc., can be found. A general approach for the development of connections, however, does not seem to exist. This leads to the assumption that in the product development process connections are not selected systematically and many connections are potentially sub-optimal.

Selecting the most suitable connection, in principle requires all existing connections to be taken into consideration and evaluated. Obviously this is, if at all possible, too time consuming. A more efficient possibility is to consider groups of connections instead of individual connections. This can be done through the use of classification schemes. Existing classification schemes classify connections according to one of the following criteria [5]:

- the working principle by which the movements between the components to be connected are restricted; in the German literature, these principles are classified in geometry, force and material continuity; if more than one principle for restricting movements is used, the connection is classified according to the last working principle that is applied [6], [7]; in the English literature, the working principles are classified in mechanical fastening, welding (physical) and adhesives (chemical) [8],
- suitability for non-destructive disconnection [9], [10],

- possible movements between the connected components (fixed – unfixed connections) [6], [7],
- manufacturing process [11].

These classification schemes show in a very detailed way specific characteristics of existing connections. However, none of them provides detailed, systematic information about the (dis-) connecting process and the number of fasteners needed.

In the work of Bauer [1] and our own work [12], several connections with different working principles for restricting movements were varied systematically by gradually integrating the fasteners into the components to be connected. That means that function carriers for connecting which were initially contained in the fastener were integrated step by step into the components to be connected. The result is shown in Figure 1, starting with components which provide only the surface for the fastener up to components which contain all function carriers which are necessary for the connection and hence can be connected without any fastener. The degree to which connecting functions are carried by the connected components is defined as *degree of integration* (Figure 1). The degree of integration is as higher as the more connection functions are performed by the connected components.

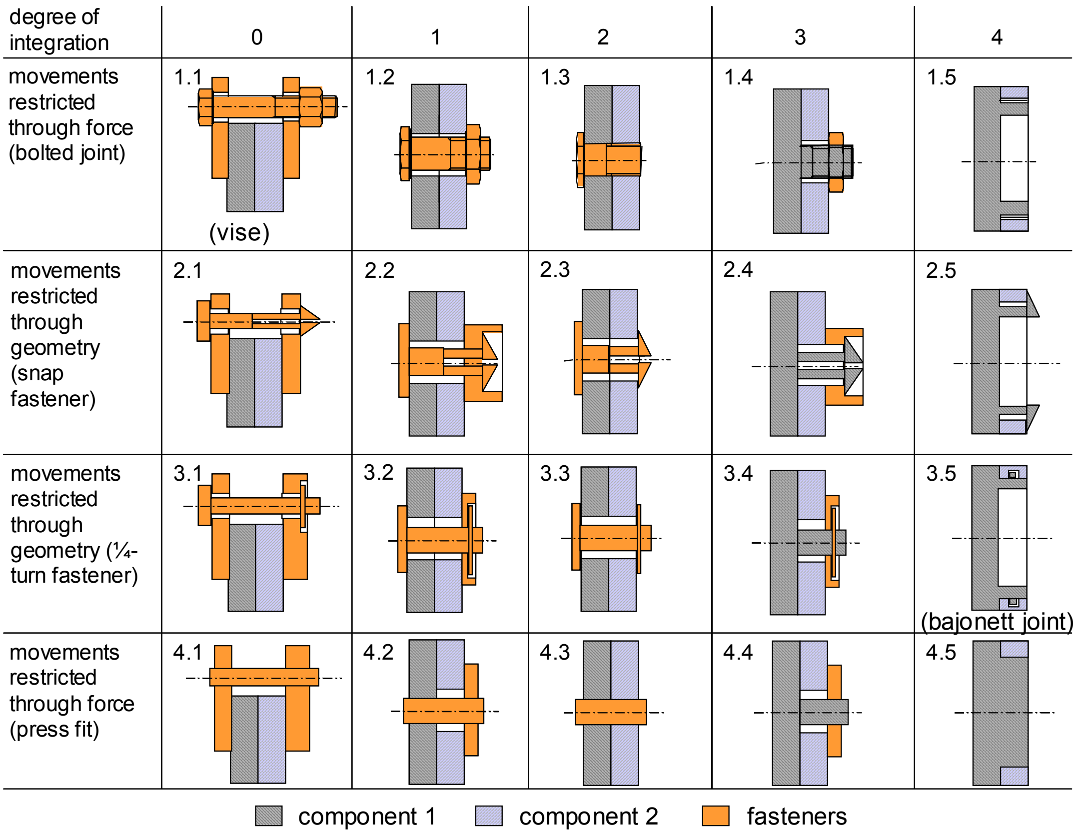


Figure 1: Classification of connections based on principles for restricting movements and the integration of connecting function carriers into the components to be connected

Regarding line by line the connections in Figure 1, it can be seen that in spite of identical working principles for restricting movements, the necessary (dis-) connecting processes of each of these connections differ. Only non-destructive disconnecting processes are considered here. The (dis-) connecting processes can be described by splitting them into *sub processes*. These sub processes describe each necessary movement, deformation etc. for (dis-) connecting components. For the connections arranged in one line (Figure 1) the connecting process and the disconnecting process are different except for the last connecting and the first disconnecting sub process. Comparing the connections column by column (identical degree of integration), these two sub processes (the last of the connecting and the first of the disconnecting process) are not identical, but the remaining sub processes are almost identical.

Hence the (dis-) connecting processes depend on both the principle for restricting movements and the degree of integration. The degree of integration in turn is determined through the structure of the connection. As can be seen in Figure 1, the structures of the different connections show components with different geometrical properties.

2 Objective

In order to support the designer in determining connections systematically a scheme is developed to provide an overview of existing types of connections. Using the classification in Figure 1 and the observation described in section 1, the different geometrical properties of the components that are to be connected are analysed for the functions they fulfil to derive possible connection principles. This can also be used to derive new variants. The focus is on fixed connections (all movements are restricted). The support to be provided should help to i.e. reduce components and consider each sub process of the necessary (dis-) connecting process.

3 Analysis of the components' geometry and their combination

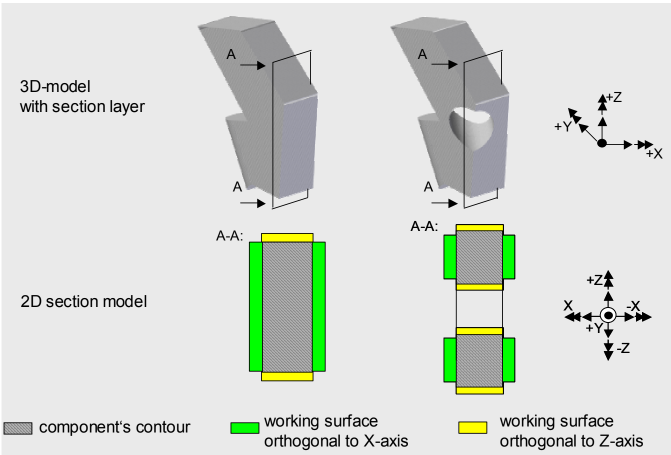


Figure 2: Working surfaces of different component types

Regarding the geometry of the connected components in Figure 1 it can be seen, that the most significant geometrical difference between the components is, that some of them are fitted with a hole while the other are not. To consider the arising consequences for restricting movements, Figure 2 shows two components of any geometry of which one is fitted with a hole while the other is not. To visualize the different characteristics for restricting movements, a section of both components is drawn according to the A-A layer. In the sections the surfaces which are available for restricting movements are identified, marked and defined as *working surfaces* (Figure 2). The particular movements which can be restricted through tightly contacting them are described in the following.

Both components possess nearly identical working surfaces that are orthogonal to the X – axis. The only difference is, that these are interrupted at the component with the hole. Tightly contacting them will restrict movements along the X – axis. A rotation around the Y – or Z –

axis only can be restricted through tightly contacting both working surfaces together. Hence, for both components the same possibilities exist for restricting movements through the working surfaces which are orthogonal to the X - axis.

The component without hole (Figure 2, left) has only two working surfaces which are orthogonal to the Z - axis, while the component with the hole (Figure 2, right) has four of them as through the hole two additional surfaces orthogonal to the Z - axis arose.

On the component without hole (Figure 2, left), movements in + Z direction only are restricted through tightly contacting the upper working surface while movements in – Z direction only are restricted through tightly contacting the lower working surface. A rotation around the Y - axis can only be restricted through tightly contacting both working surfaces together.

The additional working surfaces orthogonal to the Z – axis on the component with the hole (Figure 2, right) are positioned directly opposite each other. By tightly contacting only one of these working surfaces, the opposite working surface will possibly under clearance also be tightly contacted. In addition to the translatory movements along the Z – axis, rotation around the Y – the Z - axis will also be restricted.

The working surfaces in the hole differ from the remaining working surfaces of the components in Figure 2. Because of their direct opposition to each other, the function carriers for restricting movements need not to be split as is necessary for restricting the same movements in the component without hole (Figure 2, left).

How can this difference be explained and defined in general? While the remaining working surfaces are structured so that their normal vectors are pointing away from each other, the normal vectors of the hole’s surface(s) are pointing towards each other. The structuring of working surfaces so that their normal vectors are pointing away from each other here is defined as “convex”, while the structuring of working surfaces so that their normal vectors are pointing to each other is defined as “concave”. Depending on the structure of the working surfaces used, the components to be connected should be defined as *convex* and *concave type components*.

In the following, the possible combinations of both component types (“convex - convex”, “concave - concave”, and “convex - concave”) and the theoretical possibilities of restricting their movements will be explained.

3.1 Combination of two convex type components

By combining two convex type components with each other, the working surfaces can be classified in those which are positioned within the contact surfaces between the components to be connected (A in Figure 3, bottom) and in those which are positioned outside of this (B, C, D, E in Figure 3, bottom). Figure 3, bottom also shows the existing possibilities of contacting the working surfaces in order to restrict the remaining movements between the components, restriction of movements through tightly contacting the components (B) and through applying a load via the working surface contact (C-E) are shown in Figure 3.

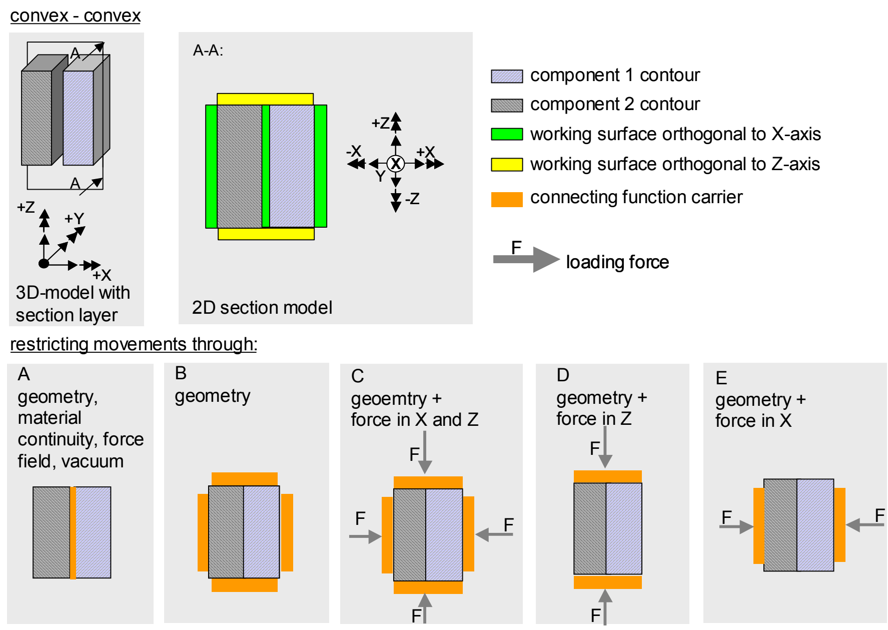


Figure 3: Combination of two convex type components and the existing possibilities of restricting the remaining movements between the components

3.2 Combination of two concave type components

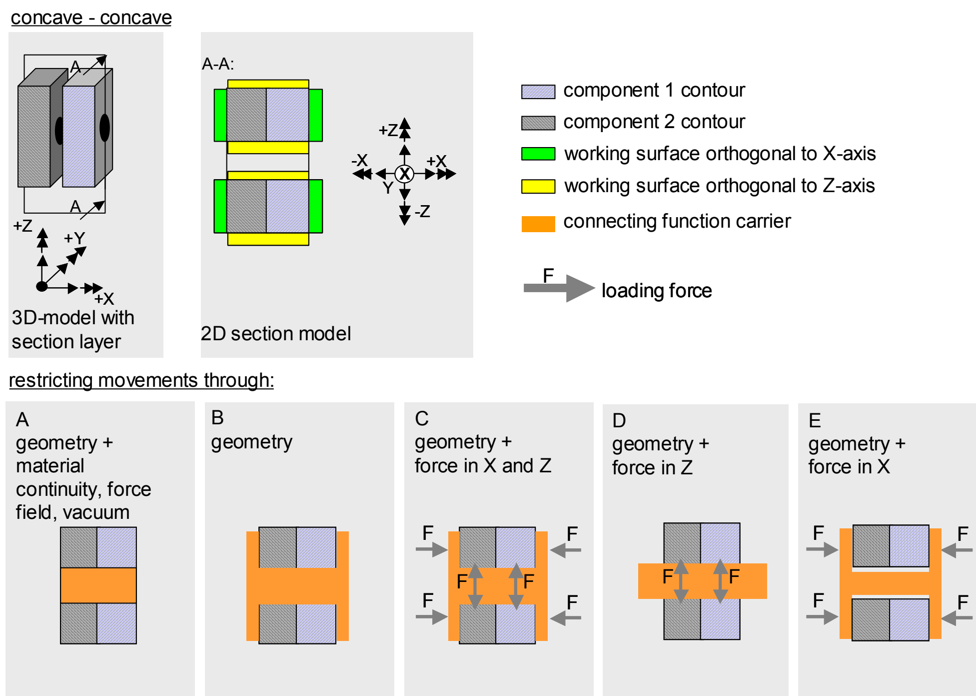


Figure 4: Combination of two concave type components and the existing possibilities of restricting the remaining movements between the components

By combining two concave type components with each other, a fastener is required. Placing this fastener into the components' hole will restrict both the translatory and the rotatory movements along and around the Y- and the Z – axis through geometry. The rotatory movement around the X-axis also can be restricted through geometry by:

- using a non-circular profile for the components' hole and for the fastener, or

- leading one or more fasteners with any geometry through more than one component hole.

Figure 4, bottom shows the existing possibilities of contacting the working surfaces in order to restrict the remaining movements between the components, restriction of movements through tightly contacting the components (B) and through applying a load via the working surface contact (C-E) are shown in Figure 4.

3.3 Combination of concave and convex type components

By combining a concave and a convex type component with each other will restrict the translatory and also, if some geometrical requirements are fulfilled (e.g. the convex type component must not be a ball) the rotational movements along and around the Y - and the Z – axis through geometry.

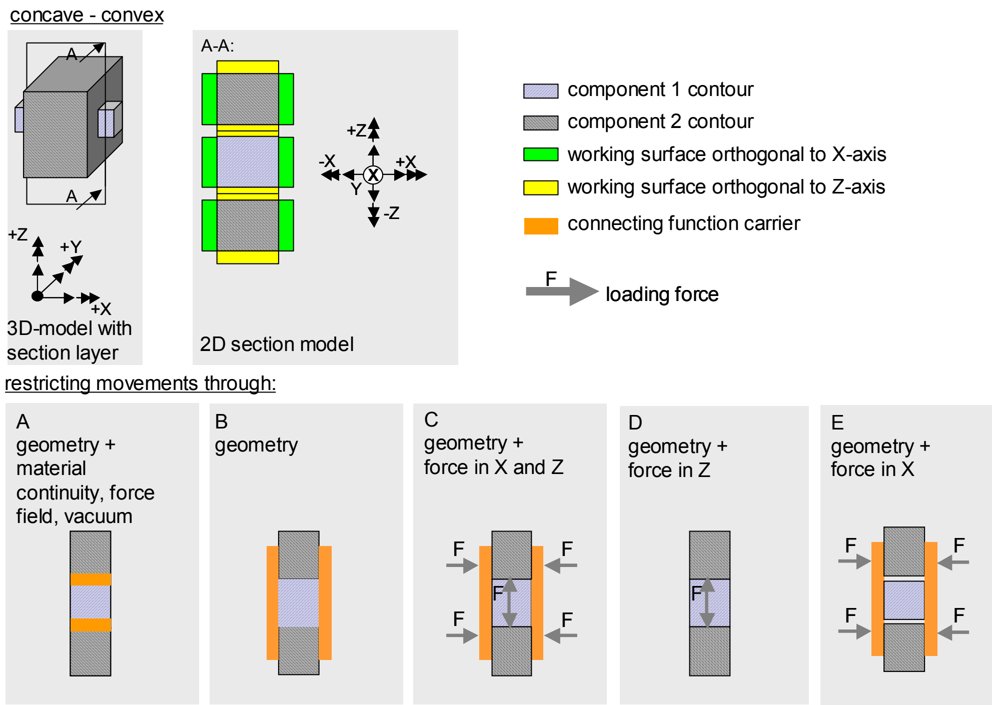


Figure 5: Combination of concave and convex type components and the existing possibilities of restricting the remaining movements between the components

The rotatory movement around the X-axis also can be restricted through geometry by:

- using a non-circular profile for the concave type components' hole and for the convex type components' contour, or
- leading the convex type component with any geometry through more than one concave type components' hole.

Figure 5 bottom shows the existing possibilities of contacting the working surfaces in order to restrict the remaining movements between the components, restriction of movements through tightly contacting the components (B) and through applying a load via the working surface contact (C-E) are shown in Figure 5.

The resulting scheme with connection principles is shown in Figure 6. It use is described in section 4.1.

4 Determining suitable connections

The aim is to determine systematically the most suitable connection that

- fulfils the connection function,
- requires as few fasteners as possible, and
- enables a low (dis-) connecting effort.

The (dis-) connecting effort is dependant on:

- the number of the required (dis-) connecting sub processes,
- the required forces and movements for performing the required (dis-) connecting sub processes.

Generally spoken, the fewer processes are required, the lower the required forces and the fewer the number of (different) movements are, the lower is the (dis-) connecting effort.

Through a systemic development process optimal connections should be realized.

4.1 First step

The aim of the first step is to realise the required function and to reduce the number of fasteners. The scheme in Figure 6 is an overview of the different connection principles which are derived from the combinations described in section 3. As for the above mentioned aims in the first instance only the connection principles are important, in the following overview (Figure 6) the forces which are added in Figure 3, Figure 4, and Figure 5 are left out. Instead of this, the areas, for which in the second step (section 4.2) the working principles have to be determined, are marked with red colour. With the scheme in Figure 6 all specific connections can be identified and derived.

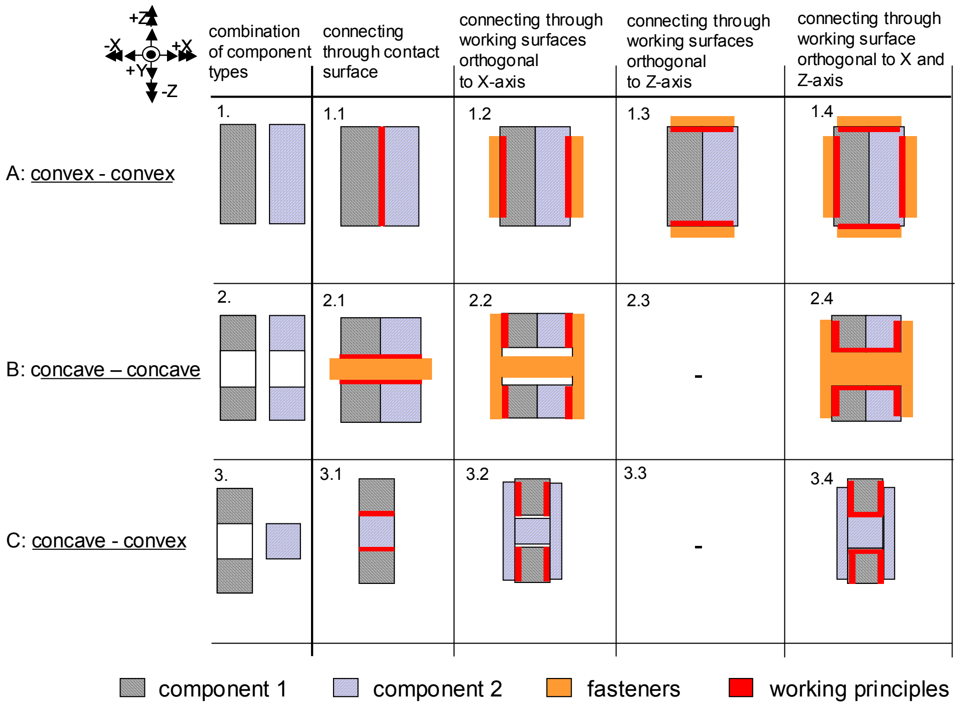


Figure 6: Scheme with connection principles and the areas for which working principles have to be determined

In Figure 7, the specific connections of Figure 1 are classified in connection principles according to Figure 6.

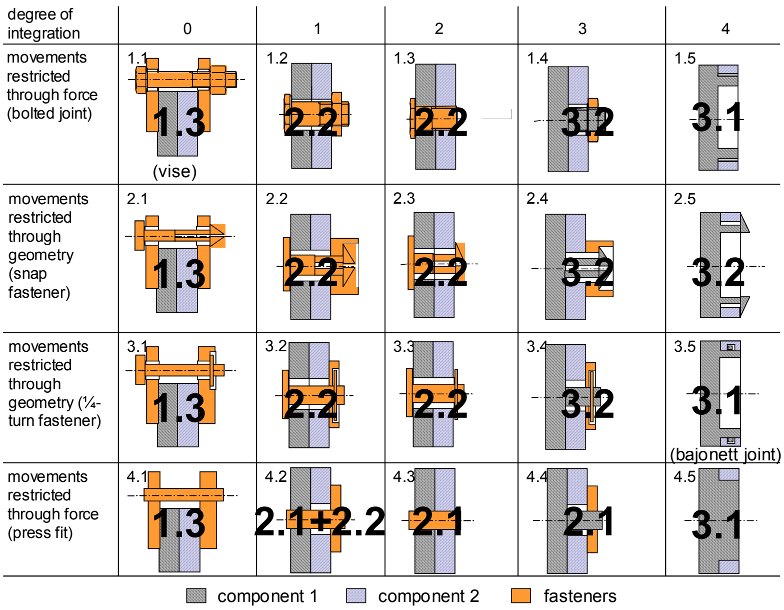


Figure 7: Classification of the specific connections in Figure 1 according to the connection principles in Figure 6

If in the connection design process an existing connection should be improved without changing the connection principle of the existing connection, the second step (section 4.2) can be started.

If the connection principle should be changed, possible connection principles will be determined with Figure 6. This can be supported by criteria such as:

- required accessibility of the components,
- available space for (dis-) assembling the components,
- desired (dis-) assembly directions of the components,
- initial geometry of components in the area for which the connection should be realized (plate or compact, rotund, cubical, etc.)
- ductility of the components material, ductility differences between the components,
- possibility of perforating the components (Are fasteners accepted?),
- aimed connection weight, etc.

After having determined the connection principle(s), the second step can be started.

4.2 Second step

Starting with the selected connection principles, concrete connections will be developed. Thereby the working principle and in turn both, the characteristics of the (dis-) connecting sub processes and the allocation of the connection function carriers to fasteners or to the components will be determined.

The working principle requirement is to enable that two surfaces will stay together for a defined period of time. The working principles which we analysed were geometry, force and mechanical fastening respectively so that the following examples are using these principles.

In the following is shown, how specific connections can be created with the connection principles 2.2 and 2.4 and the working principles basing on geometry and force.

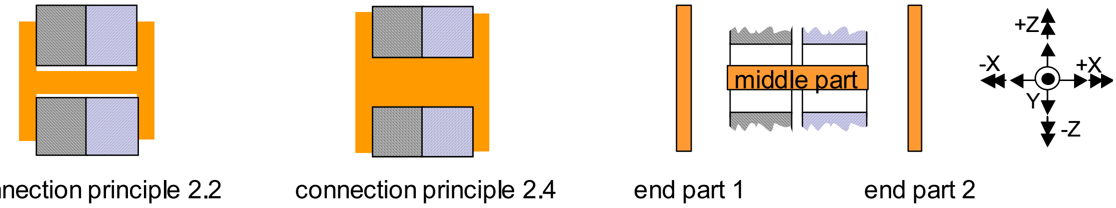


Figure 8: Split fastener of the connection principle 2.2 and 2.4 (Figure 6)

To identify the areas for which fasteners and working principles have to be determined, the abstract fastener of the chosen connection principles (2.2 and 2.4 in Figure 6) was split in the middle part and the two end parts 1 and 2 (Figure 8). For the required coupling of these parts, many working principles exist which result in different design variants of these parts. By creating and combining these parts, overall solution variants of connections arise.

end part 2 / end part 1	(dis-) conn. process (move. or def.) •connect: •disconnect:	(comb. with middlepart)	(circ. prof. !)		
(dis-) conn. process (move. or def.) •connect: •disconnect:	+Z -X +X Y -Z	•deformation •deformation	•R_{-X} •R_X	•T_X •$T_Z+T_{-Z}+T_{-X}$	•T_{-Z} •T_Z
(comb. with middlepart)	•deformation •deformation	1.1 •deformation •deformation	2.1 •R_{-X} *or* deformation •R_X *or* deformation	3.1 •T_X or deformation •$T_Z+T_{-Z}+T_{-X}$ *or* deformation	4.1 •T_{-Z} *or* deforation •T_Z *or* deformation
(circ. prof. !)	•R_X •R_{-X}	1.2 •R_X or def. •R_{-X} or def.	2.2 •R_X *or* R_{-X} •R_{-X} *or* R_X	3.2 •T_X+R_X •R_{-X}or (T_Z+T_{-Z})	4.2 •T_{-Z} *or* R_X •R_{-X} *or* T_Z
	•T_{-X} •$T_Z+T_{-Z}+T_X$	1.3 •T_{-X} *or* deformation •$T_Z+T_{-Z}+T_X$ *or* deformation	2.3 •T_{-X} *or* R_{-X} •$T_Z+T_{-Z}+T_X$ or R_X	3.3 •T_{-X} *or* T_X •$(T_Z+T_{-Z)})+T_{X/-X}$	4.3 •T_{-X} *or* T_{-Z} •$T_Z+T_{-Z}+T_X$ *or* T_Z
	•T_{-Z} •T_Z	1.4 •$T_{\_Z}$ *or* deformation •T_Z *or* deformation	2.4 •R_{-X} *or* T_{-Z} •R_X *or* T_Z	3.4 •T_X *or* T_{-Z} •$T_Z+T_{-Z}+T_{-X}$ *or* T_Z	4.4 •T_{-Z} •T_Z

move.	: movement
comb. with middlepart	: end part is combined with middle part, hence movements (T_X *or* T_{-X}) will be performed through middle part, end parts will not be charged with this movement
circ. prof. !	: restricting movements works only with circular profile
R_X	: Rotatory movement around x –axis in positive direction
T_X	: Translatory movement along x - axis in positive direction

Figure 9: Combination of end part design variants for 2.2 and 2.4 (Figure 6). The colour-code accords to Figure 6.

Therefore, first the profile of the components' hole and of the middle part as well as the number of holes and middle parts have to be determined. Either using a noncircular profile for the components' hole and for the middle part, or using more than one hole and one middle part with any profile will restrict the rotatory movement around the X - axis. If a single circular middle part is used, a rotatory movement around the X – axis remains and has to be restricted later through the end parts and the components' working surfaces orthogonal to the X -axis. So, three different general design variants for the relation between the components hole and the middle part exist.

The end parts have the function to restrict translatory and rotatory (if not restricted yet through the middle part) movements along and around the X – axis through combining the components' working surfaces orthogonal to the X - axis with the middle part. In this way the translatory movement of the middle part in + / - X direction is also restricted.

To support the process of combining the middle part design variants with the end part 1 and 2 design variants, a matrix was created with an incomplete selection of design variants for end part 1, inserted in the first column and for end part 2, inserted in the first line (Figure 9). The design variants for end part 1 and 2 are identical but mirrored because end part 1 is to the left of the middle part while end part 2 is to the right.

For the consideration of the (dis-) connecting process, the required sub-processes are briefly described in the form of the necessary movements or deformations (second line and column in Figure 9). Combining the design variants and their (dis-) connecting sub-processes, will lead to end part combinations with a short description of the resulting (dis-) connecting process. The sub process which results from leading the middle part into or out of the hole is not discretely mentioned in the matrix in Figure 9 but is here generally determined as a translatory movement in + / - X direction.

If required, an additional load in X - direction can be applied on the components' working surfaces orthogonal to the X - axis by the fastener. This can be realised e.g. by using a nut as one end part and a middle part with a circular profile and a thread. Therewith solutions as 2.1, 2.2, 2.3, and 2.4 in Figure 9 arise. For creating a connection according to connection principle 2.4 (Figure 6) an additional load in Z – direction between the middle part surface and the working surface(s) of the components' hole has to be applied.

The connection principles 3.2 and 3.4 (Figure 6) here only are mentioned briefly. In general these connection principles can be treated like 2.2 and 2.4 (Figure 6). Also the same model as shown in Figure 8 should be used with the difference that the middle part now is the convex type component and both convex type components yet are embodied through the concave type component (Figure 10). The end parts can be embodied through fasteners but they also can be integrated into the components. Similar to Figure 9, a matrix for combining the end parts was created (Figure 11).

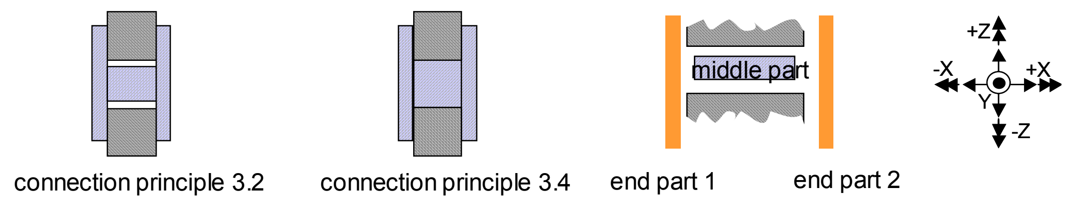
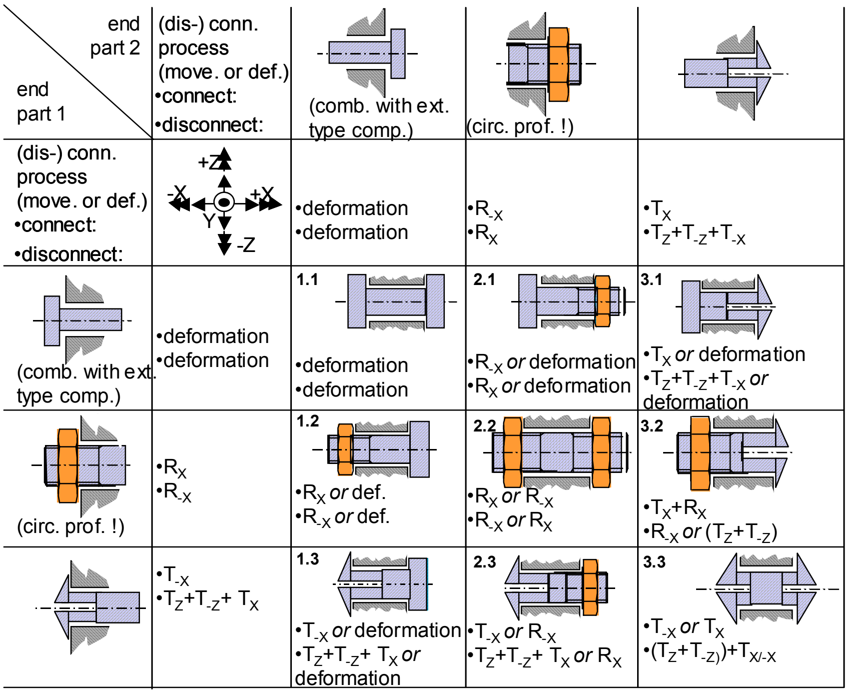


Figure 10: Split fastener of a connection principle of the connection principle 3.2 and 3.4 (Figure 6)



move.	: movement
comb. with int. type comp.	: endpart is combined with external type component, hence movements (T_X or T_{-X}) will be performed through external type component, end parts will not be charged with this movement
circ. prof. !	: restricting movements works only with circular profile
R_X	: Rotatory movement around x –axis in positive direction
T_X	: Translatory movement along x - axis in positive direction

Figure 11: Combination of end part solution variants for 3.2 and 3.4 (Figure 6). The colour-code accords to Figure 6.

If additional loads in X – or Z - direction are required, the same actions have to be taken as described above for the connection principles 2.2 and 2.4.

4.3 Design for (dis-) assembly

In the following, some connection principles listed in Figure 6 should be considered concerning the required (dis-) connecting effort.

Thereby connection principles 1.2, 1.3, and 1.4 (Figure 6) are interesting. If the working principles for restricting movements bases on geometry, all movements can be restricted e.g. by a box or a cable laid around the components to be connected. This restriction of movements in turn can be undone by removing the box or cutting the cable. If the working principle for restricting movements bases on force, all movements are restricted by applying an adequate load on the components' working surfaces. In turn for undoing the restriction of movements, only the force needs to be released. The components can then be removed easily in different directions. An additional advantage of the connection principles 1.2, 1.3, and 1.4 is that the components do not need much preparation for connection. A disadvantage is that a fastener is required which forms a (load) path around the components which needs space and increases the weight.

A better solution concerning the fastener's dimension and weight is to select another connection principle. If the connection principles 2.2 or 2.4 (Figure 6) are chosen, the fastener will penetrate the components and does not need to form a (load) path around the components any more. Hence the size and the weight decrease. However, the (dis-) connecting effort increases compared to 1.2, 1.3, and 1.4 (Figure 6), because before restricting the last remaining movement and before separating the components respectively, the fastener has to be led through the components.

To ease the (dis-) connecting process of the connection principles 2.2 (Figure 6), the components to be connected can be fitted with an open slot instead of a hole. Then, the fastener (a screw or even better a fast clamper) can be moved and removed radially in and out of the open slot and does not need to be led axially in or out of the components' hole. This is e.g. realized for the connection between the frame and the wheels of a bicycle.

Because the fastener of the connection principles 2.2 (Figure 6) consists of two end parts through which the translatory and optionally also the rotatory movements along and around the X – axis are restricted, and because the principles of both end parts are independent from each other, one end part can be designed for the connecting process while the other end part can be designed for the disconnecting process.

This was realised for a specific connection created for the DFG collaborative research centre 281 "disassembly factories" (Figure 12) [14].

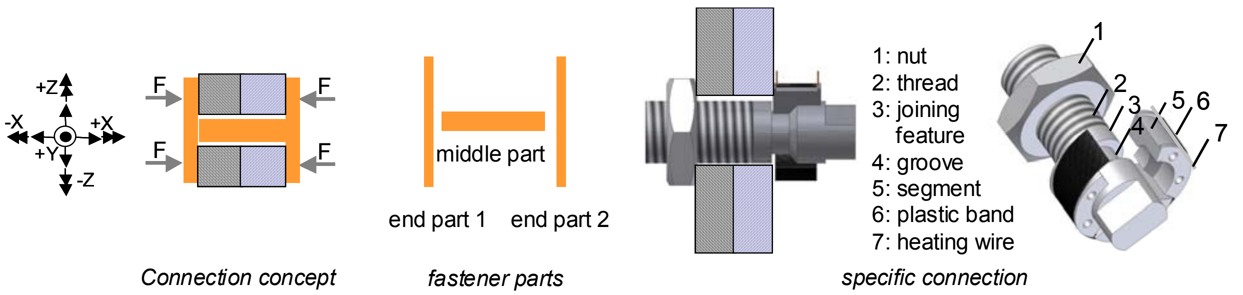


Figure 12: Specific connection optimised for both, the connecting and disconnecting process

The middle part of this fastener is a cylindrical profile. End part 1 restricts the translatory components' movements in - X - direction through an ordinary nut. The nut and the middle part are combined by the thread. End part 2 restricts the translatory components' movements in + X - direction through simple segments which are laid in a groove of the middle part and which are held in position by a plastic band. A heating wire is placed between the segments and the plastic band.

Through the thread on the nut and on the middle part, an adjustable load in X - direction can be applied on the components through which the rotatory movements around the X – axis can be restricted. Passing a current through the heating wire cuts the plastic band and causes the segments to leave their position; the movement restriction in + X direction is undone and the components can be removed in this direction. By enabling that a preload can be adjusted, end part 1 was optimised for the connecting process. By enabling that the restriction of movement can easily be undone and by including a heating wire among the plastic band, end part 2 was optimised for the (automated) disconnecting process.

Further connections which are reducing the disconnecting effort amongst others [15] were achieved by Neubert [16] and Chiodo [17]. The principles which they used will also be considered in the approach for the systematic design of connections.

4.4 Design for avoiding fasteners

Also for avoiding fasteners the scheme in Figure 6 and the matrixes in Figure 9 and Figure 11 are useful. Depending on the considered connection principle, many different possibilities exist. Some of them are shortly mentioned in the following.

On the connection principle 2.2 and 2.4 (Figure 6), fasteners can be reduced by integrating the connecting function carriers of the end parts and the middle part into one fastener (e.g. 1.1, 1.3, 3.1, 3.3, Figure 9). Still remaining fasteners can be avoided by changing the connection principle (e.g. 3.2 or 3.4, Figure 6) and integrating the connection function carriers into the convex and concave type components (e.g. 1.1, 1.3, 3.1, 3.3, Figure 11). On this topic investigations were performed by Luscher [18].

5 Conclusions

On the basis of the components geometry and the possibilities of restricting their movements, a scheme with the existing connection principles and an approach for the systematic connection design was developed.

The approach to the systematic design of connections is approximately structured as follows:

First step: Determining the connection principle(s) (Figure 6) according to the present component types and the connection requirements.

Second step: Determining the working principles and in turn the function carriers (Figure 9, Figure 11).

Third step: Evaluation, adaptation, and optimisation.

In further work, this approach will be extended in the form of a workbook which leads the designer through the process steps and offers support in optimising the (dis-) connecting process or in reducing the number of fasteners. The workbook will start at the point where two or more components have to be connected and no solution has been determined. Also lateral entry will be possible if e.g. the connection principle is already determined but an end part needs to be optimised.

The next steps are to focus on working principles which are basing on adhesive bond and to consider the third step by adding information concerning the existing connections.

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