INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITE DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

OPTIMISATION OF GRP-FLANGE JOINTS

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ABSTRACT

The dimensioning of glass fibre reinforced flange joints according to the common standards ("AD-Merkblatt N1", EN 1591 [1]) is based on the same assumptions made for steel flanges. The material properties are only considered by diminishing factors, that is why over-dimensioning becomes a problem for GRP flange joints. Three university institutes are co-operating in a research project to optimise the flange joints and the calculation standards.

GRP materials are by definition materials, which consist from at least two components [5][6][7]:

- Reinforcement fibre: the load-bearing reinforcing component. The Layout of the fibre in a component creates an anisotropic composite material, which is characterised by fibre orientation and the textile structure of the fibre systems.
- Matrix system: is used as imbedding mass for the load-bearing reinforcing component. It transmits the external loads on the fibre. Additionally, the matrix supports the fibre and is responsible for the dimensional stability under heat and resistance against liquids and gases.

The anisotropic character allows a load-appropriate design, as well as the low specific weight predestines GRP materials for highly-stressed applications in aerospace industry and mechanical engineering.

One main point of the project is the optimisation of the flange joints. The special approach used in this optimisation is the simultaneous optimisation of material properties and geometric shape. To achieve this optimisation task, two separate parametric models were created. For the geometry shape optimisation, a parametric CAD model was set up, using the CAD/CAM software "Pro/ENGINEER WILDFIRE 2". To ensure the consistency of the CAD model, different relations and boundary conditions were implemented into the CAD model. To optimise the material properties of the flange joint, a parametric FEM model was created. The model was set up using the FEM software ANSYS. This parametric model allows exchanging the material used for the different parts of the flange joint.

The mechanical behaviour of the flange joint is evaluated by using finite element analysis. To describe the GRP material properly, parameters like elastic and visco-elastic properties as well as different material layers were considered. PTFE gaskets are mostly used in GRP flange joints, therefore a material model for PTFE was also implemented to the FEM model.

The optimisation itself was done by an evolutionary algorithm, which is available without cost from a free library. Evolutionary algorithms simulate the processes of biological evolution by using so-called evolutionary operators. These operators are mutation, selection, and crossover. The algorithm works with populations of possible solutions, where every solution is defined by a set of parameters. By the application of the evolutionary operators, the algorithm creates the population (a number of solutions) of the next generation.

The optimisation process consists of a couple of steps. First step is the creation of new parameter sets (done by the algorithm); every parameter set containing geometric parameters and material parame-

ters. After that, the geometric parameters were used to regenerate the CAD models. In the next step, these models were imported into the FEM model, which was evaluated afterwards. Finally the results of the FEM evaluation are used to determine the fitness of each solution. Therefore a special evaluation algorithm (based on the Pareto approach) was applied. Using the fitness values, the algorithm calculates the parameter sets for the population of the next generation. To achieve a minimum time effort, the whole optimisation processes needed to be automated. This paper shows how different scripts were used to control this process and how the evaluation software (Pro/ENGINEER and ANSYS) is integrated in the batch process.

Keywords: evolutionary algorithms, parametric, FEM, GRP

1 INTRODUCTION

Due to high temperatures under operating conditions, the relaxation of screw forces represents a special problem when using GRP flanges. Material dependent setting processes cause a reduction of screw forces in the course of the time. The screw forces applied during assembling and during the flange dimensioning cannot be guaranteed. If the screw forces fall under a certain value, the danger of blowing out the seal exists, what usually goes ahead of a stop of the production plant.

A task of the research project represents therefore the optimisation of the flange connection, whereby especially the minimisation of the relaxation of the screw forces represents an important goal. The minimisation of the arising tensions and the deformations of the flange mark an additional goal.

In order to achieve this goal, two possible approaches were combined. The arising tensions, deformations, and the screw force relaxation can be influenced by design, i.e. geometrical parameters on the one hand. Apart from design parameters the possibility exists to exert influence on the characteristics of the flange connection by different materials and/or a different structure of the flanges when using GRP. The flanges can possess e.g. different layer thicknesses and/or the individual layers can be made of different materials. With the help of special optimisation algorithms, these parameter combinations shall be determined which fulfil the requirements best.

For the solution of optimisation problems a wide range of different methods are available, which are generally applicable or were developed particularly for the solution of special technical problems. Due to the fact, that evolutionary algorithms work robust and can universally be applied, they were used in numerous applications in industry and research [9][10][11]. When choosing a suitable method, there are different criteria, which need to be considered. By the analysis of the problem that needs to be solved, certain methods can be excluded. The optimisation problem regarded here is characterised among other things by fact, that the relation between optimisation parameters and goal criteria can not be described mathematically and structure of the solution area can’t be predicted exactly. So it has to be assumed the worst case, which means a not constant solution area with a lot of local maxima. Due to these two properties, different methods can be determined, because they can’t be applied for solving the problem. This means that methods like „hill climbing" or other gradient-based methods are excluded because they probably would get stuck in one of the local maxima and the optimisation would be finished soon at a low quality level. For the optimisation problem regarded, evolutionary algorithms were chosen, which worked successfully with the solution of optimisation problems with large and uncontinous solution area.

2 METHODS

Evolutionary algorithms are stochastic search algorithms, which simulate the natural evolution process by creating artificial populations of variants of a solution, which compete with each other. A predefined so-called fitness function is used to assign a quality value (fitness value) to each individual of the population. Due to the fact that "improved" solutions (i.e. solutions that fit the requirements better) have a better chance to reproduce, a selection pressure is built up. In this way, continuously improvement is achieved, thus realising an optimisation [8].

Basically, evolutionary algorithms work with two evolutionary operators, mutation and recombination (which also is called "crossover", See figure 1)

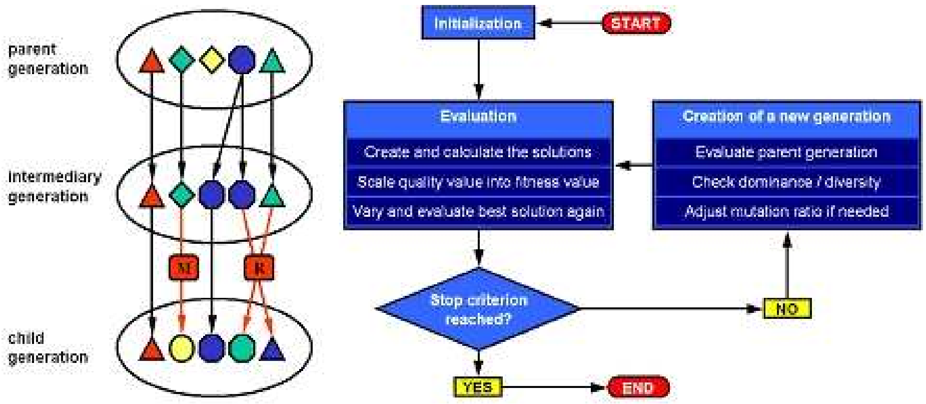

Figure 1, Evolutionary operators and evolutionary algorithms procedure

Mutation causes random modifications of a solution. It is of course not guaranteed that a better solution will be generated. When he applies intuitive ideas and methodologies, a designer works similar to mutation, because he generates "small" modifications of his solution (trial-and-error method) [4][10].

Recombination (crossover) exchanges the contents (e.g. optimisation parameters) of different solutions. This is similar to the designer's work when he, to create new solutions, combines product properties by creativity, by intuition, and by the use of his experience [10].

An evolutionary algorithm realises an intuitive search for a given target, whereby it includes a certain "intelligence", because the algorithm

- "learns" by recombination from available solutions,
- determines the benefit (fitness value) of the current solution by evaluation and selection,
- searches for new solutions by mutation as well as recombination, and
- saves the knowledge of preceding generations within the individuals (the chromosomes).

Figure 2 shows how an evolutionary algorithm finds new solutions by mutation, recombination, evaluation, and selection. The evolutionary algorithm balances the gradient methods (exploitation) and the random methods (exploration). Gradient methods (e.g. hill climbing) can resume the exploited know-how, whereas random methods (e.g. Monte Carlo method) involve the intuition. The random methods are not able to combine the results and to store the know-how. The gradient methods are frequently used as optimisation methods within FEA systems.

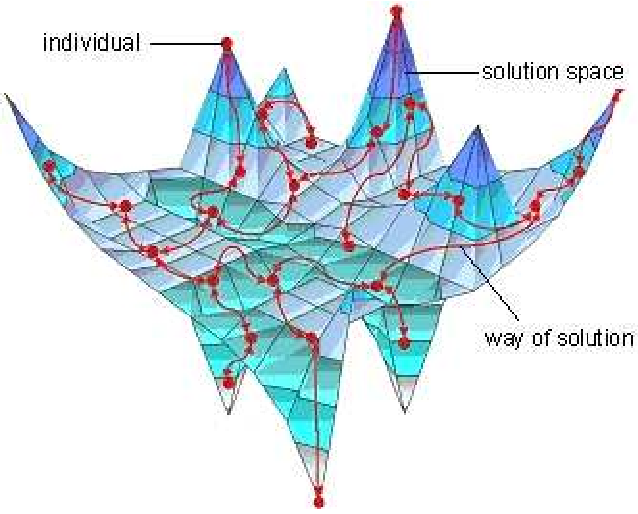

Figure 2, searching the solution space with evolutionary algorithms

3 SENSITIVITY ANALYSIS AND OPTIMISATION

In order to be able to accomplish a sensitivity analysis or an optimisation, different preliminary steps are necessary. When executing sensitivity analysis and an optimisation, a large number of variants need always to be evaluated. According to experience, the number of variants that need to be evaluated is thereby often over 1000. Most important point is thereby the setting up of an automatically running process chain, which makes the evaluation of the individual solutions possible. Essentially the following steps are necessary in the preparation:

- Choice of the optimisation parameters
- Choice of the goal criteria
- Creation of parametric CAD models
- Creation of parametric FEM models
- Creation of a process chain for automated evaluation

Optimisation Parameters

Before the creation of the parametric CAD models first the goals of the optimisation are determined and the boundary conditions arising in the employment are analysed. Based on these results those parameters are determined, with which the goals of the optimisation can be affected. An important point, which needs to be considered thereby, is the demand of the industry not to change the connection dimension to existing flanges. By this definition some important parameters are not permissible, which could have a large influence on the characteristics of the flange connection. These parameters could be considered in a second separate optimisation run.

For the optimisation of the flange connection the following parameters were selected:

- Thickness of the loose flange
- Material of the lower flange layer
- Material of the upper flange layer
- Screw size
- Outside diameters of the flat washer
- Thickness of the flat washer

- Thickness of the seal
- Material of the seal
- Collar height

The majority of the optimisation parameters was realised in the CAD system “Pro/ENGINEER WILDFIRE 2”. The parameters for the definition of the material of loose flange and seal were realised in “ANSYS 10”. The parameter „material of the upper/lower loose flange “stands thereby in each case for a certain configuration set, each set containing values as young’s modulus and poisson number.

Goal Criteria

The choice of the goal criteria essentially results from the demands made at flange connections. As previously mentioned, the screw force relaxation represents the substantial problem of the flange connection. Further the reduction of the arising tensions represents a goal of the optimisation.

For determining the stress ratios at the flange connection completely, the following characteristic values for each computed variant are determined:

- Maximum compression stress
- Tension after “von Mises”
- Tension in the screw
- Flange blade tilt
- Weight

Since the screw force relaxation represents a substantial problem, all characteristic values are not only computed when applying the loads. In the FEM model 24h load applying is simulated and afterwards the characteristic values are computed again. With those two sets of characteristic values it is possible to determine the stress reduction within 24h load application.

The last goal criterion is the weight of the entire flange connection. A more solid flange shows better stress values of course. From this it could be assumed that an optimisation without considering the weight of the flanges would result in flanges with very good stress values on the one side, but with a weight which is far above the weight of the original flange on the other side.

Parametric CAD Models

Parametric CAD models are used when it is necessary to create geometry, whose accurate dimensions in the course of the further use must be changed. This is often necessary in the context of variant design. Parametric CAD models are also used in the context of new product design, when it is necessary to evaluate certain characteristics of different modifications quickly. The creation of parametric CAD models means an increased modelling effort in relation to the conventional procedure, because additional questions (e.g. intended use, parameter) need to be clarified beforehand. Further, the actual procedure of modelling is more time-consuming, because other procedures are necessary, compared with the usual way of modelling due to the fact that in most cases relations between the used parameters must be defined.

The parametric CAD models were modelled with Pro/ENGINEER WILDFIRE 2 of the company PTC, because this system offers various possibilities for parametric modelling. This system offers a batch operation mode and is compatible to Linux. The feature of running certain functions of the CAD system in batch mode (without user interference) is essential for the execution of sensitivity analysis. Only if an automatic workflow is ensured, the necessary number of evaluations can be accomplished. The availability of the CAD software under Linux is not a real necessity, however, it facilitates the work strongly, because the individual steps of the optimisation are realised by shell scripts. Linux offers various functions within such shell scripts that made possible to work without interpreter languages such as PYTHON, Perl, TCL etc.

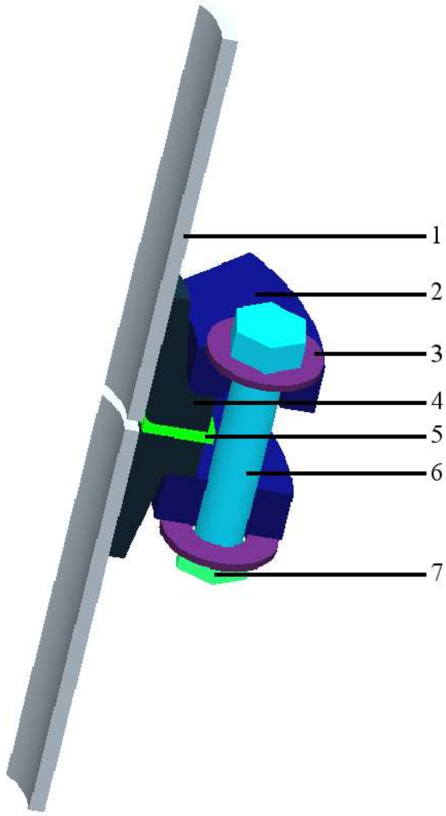

Figure 3, CAD model of the flange

For sensitivity analysis and optimisation, a CAD model of a flange connection was created (see figure 3), which consists of 9 individual parts. The model consists of a collar (see No. 4 in figure 3) of pipe (1), 3-layer flange (2) (upper layer, intermediate layer and lower layer) as well as the connections elements nut (7), screw (6) and flat washer (3). All individual parts were created parametrically in such a way that the optimisation parameters (see chapter 2.3) could be applied. The necessary relations between the parameters were defined in the proprietary programming language Pro/PROGRAM. By using symmetry conditions at the flange, the model of the flange connection could be reduced to an eighth model. This has the advantage that in the computation with ANSYS an eighth of the junctions must be only computed, so the computing time was reduced significantly.

For the processing of the sensitivity analysis and the optimisation it was necessary to pass the current parameter values to the CAD system over as simply as possible. In Pro/ENGINEER there are different ways to realise this. From our view, the simplest way is the supply of the current values in a separate file. During the creation of the different variants, the parameter values of this file are imported and assigned to the individual CAD parts considering the stored relations and boundary conditions. In the next step, the individual parts are built into an assembly. This step is not really necessary, but it provides an easy way to do a collision check whereby invalid variants can be eliminated. After passing the collision check successful, the individual parts are exported into a neutral format (IGES).

As previously mentioned, the automated creation of the CAD models is necessary. Therefor, the following steps need to be automated:

- Importing parameter values
- Creation of the individual parts
- Creation of the assembling

- Collision check
- Export into neutral format

Pro/ENGINEER allows the automation of repeated work with so-called “Trail” files. A “Trail” file contains all needed function calls to fulfil a certain task. With correct configuration, the above-mentioned steps can completely be automated, with the help of such Trail files. Only this functionality allows performing a sensitivity analysis or a parameter optimisation in an acceptable period of time.

Parametric FEM Models

The parametric FEM models are provided by our project partner from the Technical University Clausthal. For the sensitivity analyses and the optimisation static FEM models can't be used. Because on the one hand variable geometry shall be used (see chapter 2.5) and on the other hand different material configurations sets for the upper layer and the lower layer of the loose flange shall be available.

Each material configuration represents thereby a special flange. For the determination of the material-mechanical characteristic values of the flanges, 3-point bending test as well as tensile-pressure tests were done. The flange samples examined thereby differ in number of glass fibre materials as well as in the arrangement of these materials. Results of the attempts are characteristic values such as young's modulus and poisson number, which were then stored in the respective material configurations.

The processes of the FEM computation can be automated in ANSYS. The whole process is controlled by a script, which automates the following steps:

- Importing the geometry models (IGES)
- Assigning the material indices
- Meshing
- Definition of the contacts
- Definition of the boundary conditions
- Solving
- Evaluating the results

Process Chain for Automated Optimisation

After the definition of the optimisation parameters as well as the creation of the parametric CAD and the FEM models, these are merged into a process chain for the evaluation of the different variants. This process chain is built up modularly and consists of individual scripts. In order to accomplish an optimisation, the process chain must automate the following steps:

- Parameters conversion
- CAD models creation
- FEM model calculation
- Evaluation

The conversion represents the first step of the process chain. In this step the optimisation parameters generated by the optimisation algorithm are processed. From these parameters, the parameter values for the CAD model as well as the FEM model are determined and converted into a readable format for the respective program. The parameter information is stored in simple text files for the sake of simplicity.

In a further step the CAD models for the current optimisation parameters are created, whereby the parameters converted in the preceding step were accessed. The CAD models are exported into a neutral interface format, in order to be able to use it in the next step, the FEM computation.

The FEM part performs the computation of the mechanical characteristics of the respective variants. In this step the exported CAD models as well as the FEM parameter file are imported and the parametric FEM model is created on this basis. The FEM computation supplies the goal criteria, as well as other values.

The last step within the process chain is the evaluation of the computed variants. The goal criteria are used in order to perform a Pareto evaluation. The Pareto evaluation determines numerical values (the so-called fitness value), which represents the quality for each computed variant.

The fitness values determined by the Pareto evaluation are finally passed to the optimisation algorithm. By application of the evolutionary operators (see chapter 2) the algorithm produces new variants, which are evaluated in the same way.

4 SENSITIVITY ANALYSIS

With the execution of the sensitivity analysis, the goal of reducing the complexity of the provided computer model is pursued, by determining the parameters that have an important influence on the behaviour of the flange connection. Reducing the number of optimisation parameters also reduces the size of the solution area for the optimisation afterwards, which makes a more exact investigation possible (with same effort of time).

For executing a sensitivity analysis a database is needed, on whose basis the correlation characteristic values can be determined. The database contains thereby a multiplicity to data sets, which contain optimisation parameters and associated goal criteria in each case. The result quality attainable with a sensitivity analysis essentially depends thereby on two factors.

- Number of data sets
- Distribution within the solution space

The number of data sets should be sufficiently large. If the sensitivity analysis is based on fewer data sets, the determined results are provided with an accordingly large factor of uncertainty. If the number of data records rises, the result quality usually increases too. It is to be noted, however that the number of data sets is to be always regarded together with the distribution of the data sets. If the distribution of the data records is unfavourable, the attainable results themselves are not representative even if a large number of data sets are used. The distribution of the data records over the solution area is ideally adapted to the condition of the solution area. If there are areas in the solution space, were small changes of the parameters results in large changes of the goal criteria, then more data sets should be used. In areas were large changes of the parameters mean only small changes of the goal criteria, fewer data sets need to be raised.

For the creation of the database, the respective parameter range for the 9 optimisation parameters is specified. It’s to be considered that only a few parameters from the possible parameter range can be selected. As to be seen in table 1, for each parameter 1-4 concrete values are considered.

Table 1. Parameters for sensitivity analysis

parameter	***min***	***max***	***steps***
thickness flange	5	35	4
screw type	1	3	2
material number upper layer	1	13	2
material number lower layer	1	12	2
thickness seal	1	10	2
material number seal	1	4	4

height collar	10	40	2
Width flat washer	3	25	3
thickness flat washer	1	10	3
4608 variants; 10min per variant => about **32** days			

The attainable quality of the results could be surely increased with more considered values. However the used number of values already forms a database with approx. 4600 data records. One accepts a time of only 10 minutes for the complete evaluation. This already means a computing time of approximately 32 days. Since the individual evaluations are independent of each other, sensitivity analyses represent ideal application for distributed counting. A manual computation of all parameter sets (approx. 4,600) of the analysis of sensitivity is not possible, for the execution of the sensitivity analysis the process chain represented in chapter 3.7 is used. This process chain calls all scripts needed for the computation and then stores the computation results for each parameter combination in a database.

The result of the sensitivity analysis is to be seen in illustration 2. The meaning of the used abbreviations is described in table 2.

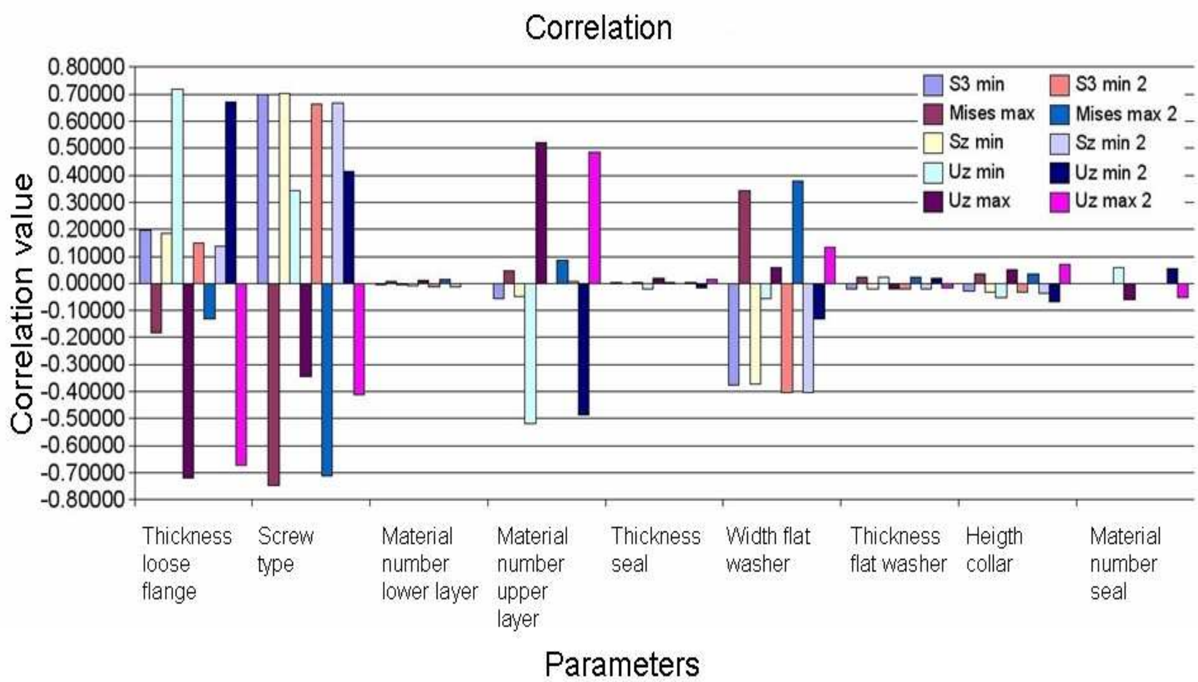

Figure 4, Sensitivity analysis

Table 2. Parameters for sensitivity analysis

abbreviations	***explanation***
S3	Pressure stress
Mises	Stress after Mises
Sz	Stress in the direction of load exposure
Uz	Deformation

Figure 4 shows that not all of the selected parameters have an influence on the characteristics of the flange connection. Above all, the parameters flange height, screw type. The parameter "screw type" stands here for different screw sizes of M6 to M20 .

A little bit smaller, but nevertheless relevant influence for properties of the flange connection are the parameters „material upper layer“ and „width flat washer“. The parameter „material upper layer“ defines the material indices in the highest layer of the 3 layer loose flange model. Both parameters contribute the characteristics of the flange connection substantially, since they are for the force application of substantial importance. The bigger the flat washer, the smaller the arising surface pressure. In addition, the material of the highest loose flange layer determines the characteristics of the flange connection relevant.

In comparison to this, the influence of the material of the lower loose flange layer is completely different. The material in this layer has as well as no influence on the characteristics of the flange connection. This could be justified in the fact that the contact area between lower layer and collar is substantially larger, than the contact area between upper layer and flat washer, which results in a surface pressure substantially smaller in the lower contact.

In addition figure 4 shows that the parameters „thickness seal“, „thickness flat washer“, „height collar “and “material seal” do not affect the characteristics of the flange connection. From the results of the accomplished sensitivity analysis the appropriate conclusions for the following optimisation can be drawn. Not necessarily all 9 parameters need to be used for the optimisation starting up in the next step. For this reason, the parameters, which aren't regarded any longer, are the parameters “material seal”, “thickness seal” and „thickness flat washer“. The parameters „materials number lower layer“ “height collar” are considered in modified form in the optimisation.

5 OPTIMISATION

The optimisation has the goal to find those solutions in the solution area that fulfil the goal criteria best. The optimisation runs thereby similarly to the analysis of sensitivity. The substantial difference is that in case of the sensitivity analysis all variants that shall be computed are a known beforehand and an evaluation of the computed variants is not done (the computed values are simply stored in a database. Instead the variants are generated by an evolutionary algorithm and evaluated afterwards by a Pareto based procedure.

For the smooth operational sequence of the optimisation, the process chain was set up within a special management system. This allows to extend or to change the process easily. Further this system offers the possibility of supervising and simple evaluation of active runs.

For the optimisation, the optimisation parameters that shall be used are declared within a separate configuration file. Apart from the parameter name, further data are specified such as minimum value, maximum value, and increment. The configuration file also contains a few more information, e.g. mutation probability, crossover probability, methods for mutation and crossover that shall be used. For the optimisation, a mutation probability of 0.1 was chosen, which means that 10% of the individuals are mutated. The crossover probability is selected with 0.8, whereby within the production of a new generation 80% of the individuals are combined. For the optimisation a maximum generation number of 200 with in each case 40 individuals was set. The number of individuals maximally computed is 8000. Further the convergence threshold is set to 99%, which means that the optimisation stops before reaching the maximum generation number, if the convergence level is reached earlier.

For evaluation a Pareto based method, which makes an unweighted multi-criteria evaluation possible, is used. Pareto based approaches are often used in the field of multi criteria optimisation. All approaches are based on the so called pareto-optimum, which is named after Vilfredo Pareto, who was a french-italian sociologist, economist and philosopher. In relation to other procedures like weighted goal functions this has the advantage that optimisation algorithm is not forced into a certain direction, which probably prevents the algorithm of finding certain good solution. Pareto based methods are able to determine those variants, which exceed the remaining variants in all goal criteria and represent the actually best variants [2][3]. The results determined thereby are not absolute, but always dependent on all regarded variants. If further variants are added, all variants must always be evaluated again.

6 CONCLUSION

The approach introduced in this work represents a possible of realisation of the very complex topic of the computation and optimisation of GRP parts. In addition, FEM computation of GRP parts was combined with an efficient optimisation algorithm and a procedure for unweighted free multi-criteria evaluation.

The used process chain for automatic optimisation can easily be extended with further CAD and FEM models. Additional optimisation parameters or goal criteria can be added by the modular structure in a simple manner. Also an extension by additional computation software is possible, whereby further criteria can be considered, too.

An extension of the optimisation appears particularly meaningful in two points. On the one hand the number of geometrical optimisation parameters should be extended. The actually used parameters represent the restriction of the industrial partners involved in the project. For this reason, no parameters (e.g. number of screws, pitch diameter) are contained, which concerns the junction points to already existing flanges. One the other hand it appears meaningfully above to fully develop all material-technical parameters. In this range a large optimisation potential exists. The biggest problem is that the calculation models needed for the simulation are missing. In certain cases this can become balanced by empirical attempts. However, extensive test series would be necessary, which is impossible to realise in most cases.

ACKNOWLEDGMENT

This project (AiF 14235 BG/2 „Auslegung von Flanschverbindungen aus glasfaserverstärktem Kunststoff (GFK) für die chemische Industrie) was supported by the „Bundesministeriums für Wirtschaft und Arbeit (BMWA)“ within the working group „industrielle Forschungsvereinigungen „Otto von Guericke“ e.V. (AiF)“

REFERENCES

[1] AD-Merkblatt N1 Druckbehälter aus glasfaserverstärkten Kunststoffen (GFK).

[2] J. Anderson: “A survey of multiobjective optimization in engineering design”, Technical Report, Linköping University.

[3] H. Boll: „Evolutionäre Verfahren zur Optimierung von Produktionsplänen mittels impliziter Kooperation“, Dissertation, 2003.

[4] E. Elbeltagia, T. Hegazyb, D. Griersonb: ”Comparison among five evolutionary-based optimization algorithms”, Advanced Engineering Informatics, Vol. 19, 43-53, 2005.

[5] M. Flemming, S. Roth, G. Ziegmann: „Faserverbundbauweisen – Fasern und Matrices“, Spinger-Verlag, Heildelberg, 1996.

[6] M. Flemming, S. Roth, G. Ziegmann: „Faserverbundbauweisen – Halbzeuge und Bauweisen“, Spinger-Verlag, Heildelberg, 1996.

[7] M. Flemming, S. Roth, G. Ziegmann: „Faserverbundbauweisen: Fertigungsverfahren mit duroplastischer Matrix“, Spinger-Verlag, Heildelberg, 1998.

[8] A. Jordan: „Entwickeln eines anwenderfreundlichen Optimierungsalgorithmus auf der Basis Genetischer Algorithmen“, Otto-von-Guericke-Universität Magdeburg, Lehrstuhl für Maschinenbauinformatik, Diplomarbeit, 2000.

[9] P. Makk, B. Wegner, S. Vajna, T. Bercsey, H. Kickermann, P. Kellner: „Rechnerunterstützte Optimierung von Zylindereinlasskanälen mit Genetischen Algorithmen“, ICED 99, München, August 24-26, 1999.

[10] P. Pohlheim: „Evolutionäre Algorithmen“, Springer Verlag, Berlin, 1999.

[11] B. Wegner: "Autogenetische Konstruktionstheorie - Ein Beitrag für eine erweiterte Konstruktionstheorie auf der Basis Evolutionärer Algorithmen", Magdeburg, Dissertation Otto-von-Guericke-Universität, 1999.

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