Development of design rules for adhesive bonded joints

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This article deals with the development of design rules for structural adhesive bonded joints. In daily practice engineers are confronted with the problem to verify the reliability of their designs. This can be done with use of an experimental programme, but for the marine, transport, building and civil engineering sectors this will not be an option, because it is too expensive and time consuming. The use of design rules might be an alternative, but current guidelines for structural adhesive bonded joints do not guarantee the reliability. To develop design rules that meet the required level of reliability, new approaches have to be used. Such a systematic approach is presented in this article. It is based on the current structural adhesive bonding technology and on structural reliability methods. Partial factors are used to take the required reliability level into account. Additional conversion factors are introduced to cover the effects of ageing. Methods are discussed how to calibrate these factors. To illustrate the developed approach, examples of calibrating design rules for metal overlap joints with epoxy and polyurethane adhesives are presented.

Key words: adhesive bonded joints, reliability, design rules

1 Introduction

Today, there is a growing interest in industry to use adhesive bonded joints for structural applications. This joining method offers advantages over more conventional methods such as welding, riveting and bolting. Substantial economic profits can be made by the development of new design solutions. By using adhesive bonded joints, new materials can be applied and there is the ability to work out novel structural configurations. A good example of this development is the sandwich panel. Different types of materials for the faces and core are combined to form the layered structure and the faces can be reinforced locally by bonding stiffeners at critical locations. The developments of such new design solutions require new design concepts.

For structural applications of adhesive bonded joints, present practice is confronted with the absence of reliable design rules. Only experiments are appropriate to validate if the required reliability level is reached. Various reasons can be put forward. A large variety of potential prediction models are discussed by researchers over the years, but without agreement. There is still a lack of knowledge about failure mechanisms, ageing and the stochastic nature of the strength. Also the

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experience with the selection of adhesive bonding systems, the structural design of a joint and the development of manufacturing processes is limited. The key reason is that the adhesive bonding technology is faced with difficulties to predict the structural behaviour and durability of adhesive bonded joints within coherent preferably standardized approaches.

Another reason for the absence of design rules has a historical background. The first designs of structural adhesive bonded joints were made in aerospace industry. From the period after the Second World War up till now the aerospace airworthiness authorities have only accepted design solutions validated with use of extensive test programmes. It will normally take several years to develop a solution that meets the high level of requirements. There is no urge to optimise an accepted design solution, because the costs will be higher than the profits. This situation hinders the development of design rules for validation. In the automotive industry adhesive bonded joints were introduced during the 1980's. Compared to aerospace applications, the manufacturing process had to be cheaper. This initiated the development of other adhesive bonding systems, but still the design method based on tests has been used to validate design solutions. The high costs of tests can be afforded easily, because of the large scale of production. In both automotive as well as the aerospace industry a driving force is missing to develop design rules for validation.

In other sectors of industry like marine, transport (other than automotive), building and civil engineering new design solutions have to be developed with a limited budget and within a short period of time. This is because these unique design solutions are custom-made and are mostly produced in small series. The use of extensive test programmes will be too expensive and time consuming. The only alternative to validate design solutions of adhesive bonded joints is to make use of reliable design rules.

Reliable design rules are based on two essential issues: a prediction model and a structural reliability method. The prediction model has to give a proper description of the structural behaviour under given mechanical and environmental actions. The structural reliability method has to guarantee the reliability level of the structure. Reliability is defined as the ability to fulfil prescribed requirements during a specified lifetime. It is equal to the probability that the structure will not fail and will perform its intended function. This means that the stochastic nature of the strength should be taken into account. To develop reliable design rules these two subjects have to be combined systematically.

The objective of the PhD-study performed by the author [1], was to develop a systematic approach to arrive at reliable design rules for structural adhesive bonded joints. To illustrate the potential of this approach, the study focuses on the joining of metals under short-term static load conditions and under high humidity conditions. Both the structural behaviour as well as the degradation behaviour of adhesive bonded joints are considered. The systematic approach is formulated in such a way that it can be used for all kinds of adhesive bonded joints under various actions. The presented systematic approach is based on current knowledge about the behaviour of adhesive bonded joints and on structural reliability methods widely accepted nowadays. In this article an outline of the results of the systematic approach developed in the PhD-study, is given.

2 Design rules for structural adhesive bonded joints

In the old days the experience of ancient builders guaranteed the reliability of structures. But the use of new materials and other applications forced modern builders to change their design philosophy. Engineers have developed new techniques to design by calculation. Modern design rules based on the partial factor, make use of structural reliability methods to reach the required targets of reliability, and are based on limit states.

The limit state is defined as the condition in which the structural component is no longer capable to fulfil its functions under given action. A mathematical presentation is given by the limit state function defined as the difference between the resistance (R) and the action effect (S):

$$Z = R - S \tag{1}$$

As long as $Z > 0$ no failure will occur, while for $Z < 0$ the structure fails; the limit state is reached for $Z = 0$. Both the resistance and the action effect are regarded as stochastic variables, which can be represented by their probability functions $f_R(r)$ and $f_S(s)$ respectively. If the resistance and the action effect are independent, their combined probability function is defined as $f_R(r) \cdot f_S(s)$. This function can be graphically presented by contours in its R-S plane, as indicated in figure 1. The probability of failure $P(\cdot)$ is equal to the capacity of the combined probability function for which $Z < 0$. Mathematically this probability of failure is given by:

$$P(Z < 0) = \iint\limits_{Z<0} f_R(r) \cdot f_S(s) \cdot dr ds \tag{2}$$

To solve it, several probabilistic methods have been developed [2]. With use of these methods it is now possible to quantify the reliability of a structural component.

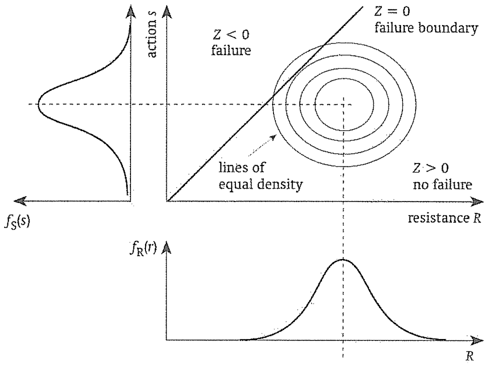

Figure 1. Statistical presentation of the limit state concept

Instead of presenting the results of the probabilistic methods in terms of probability of failure, the reliability index β is commonly used. The relation between the probability of failure $P(Z < 0)$ and the reliability index β is given by:

$$\mathrm{P}(Z < 0) = \Phi(-\beta) \tag{3}$$

where Φ is the standard normal distribution function. For the static load case and an intended lifetime of 50 years a target value $\beta = 3.8$ is defined [3], which corresponds with a failure probability of 0.00007.

The partial factor approach is mostly used for design. The reliability of a component has to be validated by comparing the characteristic values of the action effect S_k and the resistance R_k:

$$\gamma_\mathrm{S} \cdot S_\mathrm{k} \leq \frac{\eta \cdot R_\mathrm{k}}{\gamma_\mathrm{R}} \tag{4}$$

where γ_S and γ_R are partial factors for the action effect and the resistance respectively. These partial factors take the stochastic nature of the action effect and the resistance into account. The conversion factor η corrects the resistance for durability effects. The characteristic values are mostly based on statistical means. In case of for example the action wind load the characteristic value might be equal to the load that occurs once in a 50 years period. Comparable definitions are given for the characteristic value of the resistance. To validate a design of an adhesive bonded joint the characteristic value of the action effect S_k and matching partial factor γ_S can be taken from existing standards, as for example described in Eurocode 1 [3]. The characteristic value of the resistance R_k has to be based on a prediction model, but the matching partial factor γ_R and conversion factor η are still not generally available.

The value of the partial factor for the resistance γ_R has to be determined by calibration. In the past this was mostly done by engineering judgement, but probabilistic analyses enable the use of additional quantitative information. Since the action effect and resistance are completely separated by the partial factor approach the target probability defined by equation 3 is weighted. The design value of the resistance R_d, which represents the right hand side of equation 4, is defined in such a way that the probability of having a more unfavourable value equals:

$$\mathrm{P}(R > R_\mathrm{d}) = \Phi(\alpha_\mathrm{R}\beta) \tag{5}$$

The quint essence of the method based on probabilistic considerations, is the fixing of α_R to a value equal of 0.8 [3]. This value seems to be valid for a wide field of applications.

With use of equation 5 it is now possible to calculate the design value of the resistance R_d. By comparing this value with the matching characteristic value calculated with the predicting model, the partial factor is determined as follows:

$$\gamma_\mathrm{R} = \frac{R_\mathrm{k}}{R_\mathrm{d}} \tag{6}$$

The above given simplified presentation to determine the partial factor is the usual method of calibrating a design rule based on probabilistic techniques.

Also the value of the conversion factor has to be determined by calibration. This can be done by engineering judgement, but probabilistic analyses open possibilities of getting additional quantitative information. A simple approximation can be made on basis of the degraded resistance at the end of the assumed lifetime $R(t_p)$. Comparing this value with the initial value $R(t_0)$ gives the value of the conversion factor:

$$\eta = \frac{R(t_p)}{R(t_0)} \tag{7}$$

Both the initial and degraded values of the resistance have to be determined on basis of tests.

3 Example of the calibration of the partial factor γ_R for overlap joints

In this example a design rule for overlap joints with an epoxy adhesive is calibrated. The value of the partial factor γ_R is determined by a probabilistic technique, which compares experimental strength values with matching values according to a proposed prediction model.

Tests were performed on 25 mm wide double strap joints, see figure 2, with steel adherends and a toughened cold cured two-component epoxy adhesive. Three overlap lengths (10, 20 and 40 mm) and three adherend thicknesses (2, 4 and 6 mm) were studied. The specimens were axial loaded in tension and the load-displacement curves were recorded. An overview of failure loads is given in figure 3. For each combination of overlap length and adherend thickness 6 or 7 tests were performed. It was found that the scatterband within each series equals approximately 5%.

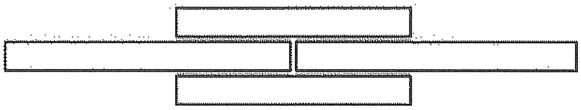

Figure 2. Schematic side view double strap joint

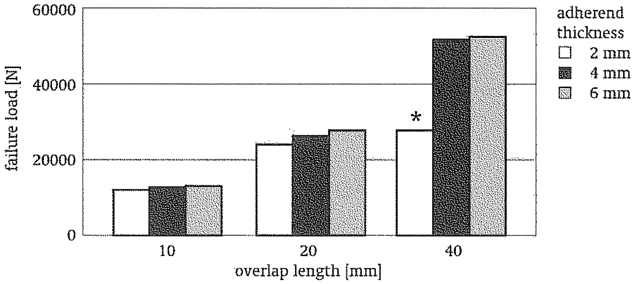

Figure 3. Overview of the mean value of the failure loads (plastic failure of the adherend)*

The prediction model has to be based on a failure criterion, on test methods to determine the adhesive properties and a model to calculate the stress and strain state within the adhesive bondline. Since adhesive failure occured, a pressure dependent yield criterion as used for polymers [4], seems to be fairly straightforward. This criterion is based on the assumption that a polymer yields or fails at a higher level as the hydrostatic pressure increases. Final failure occurs as soon as an ultimate strain is reached. An advantage of this yield criterion is that it can be used to model physical non-linear behaviour of the adhesive.

The input of this yield criterion and of the model to calculate the stress and strain state in the adhesive bondline, has to be determined by testing. Proper tensile and compression tests will provide values for the Young's modulus, the Poisson's ratio, the stress-strain curve, the ratio between compressive and tensile stresses, and the ultimate tensile strain. Useful and well established procedures to determine these properties are standardised by the American Society for Testing and Materials [5] and [6]. For the adhesive considered the mean tensile stress-strain curve was experimentally determined. In figure 4 the mean curve for the adhesive considered is given. For the chosen pressure dependent yield criterion also the ratio between compressive and tensile stresses is determined and the Poisson's ratio is calculated by comparing the transverse and axial strains within the unidirectional tensile test.

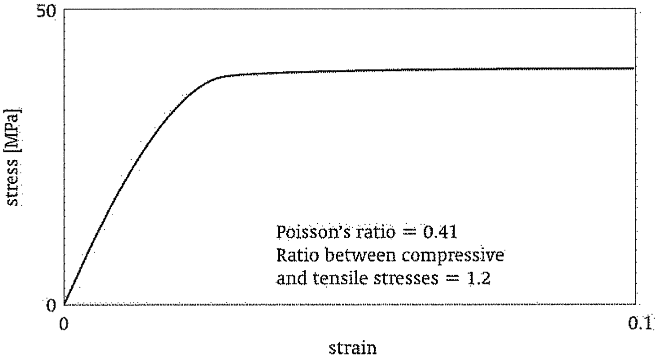

Figure 4. Stress-strain curve of the toughened cold cured two-component epoxy adhesive

The selected approach to calculate the stress and strain state in the adhesive bondline models the adherends as plates and the bondline as springs. The latter have to connect the adherends in longitudinal and transverse direction to be able to determine the shear and transverse normal stresses respectively. Goland and Reissner also used this modelling in their well known classical solution which was generalized by the author [1]. Instead of deriving a closed-form solution, a set of differential equations is formulated together with the proper boundary conditions. This boundary value problem can be solved with a numerical algorithm. To model the physical non-linear behaviour of the adhesive, the prediction model was extended by a special developed iteration procedure.

Comparison with test results validated the proposed prediction model. In figure 5 the load deflection curve is given for the case of 4 mm thick adherends and a 20 mm overlap length. It is concluded that the physical non-linear model gives rather good predictions.

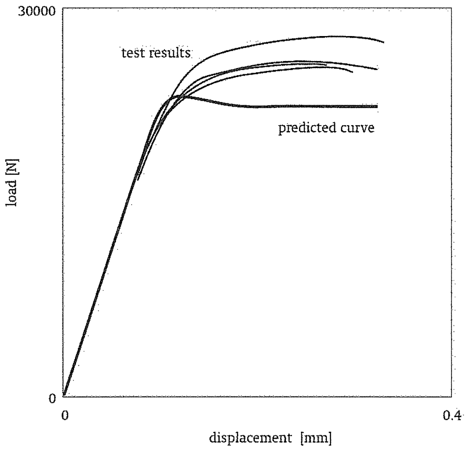

Figure 5. Comparison of prediction model and test results

Essential in the calibration procedure is the comparison of the set of data with the matching resistance predicted by the proposed model. The set of data comprises the test results $R_{\mathrm{tests},i}$ as presented in figure 3. The corresponding resistances $R_{\mathrm{pm},i}$ are calculated with the prediction model, by using the nominal values of the dimensions and the stress-strain curve of figure 4. The graph shown in figure 6, with the set of test data on the vertical axis and the corresponding calculated values on the horizontal axis, indicates that the prediction model fits rather well with the test data. The differences provide additional quantitative information, which is used to perform a statistical analysis.

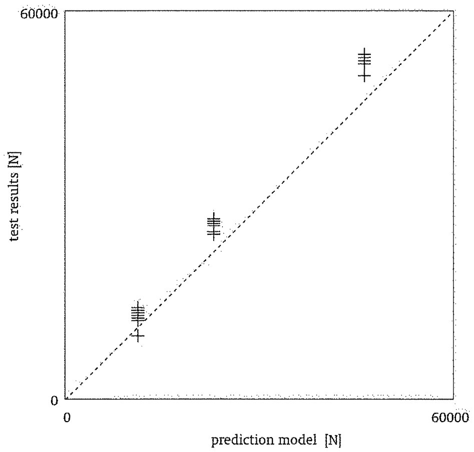

Figure 6. Comparison of test data with corresponding calculated values

To quantify the differences between the set of test data and the matching values predicted by the model, multiplication factors K_i for all data points i are determined as follows:

$$R_{\text{test};i} = K_i \cdot R_{\text{pm};i} \tag{8}$$

Once all the multiplication factors are calculated, their statistical distribution function is determined. The estimated mean and standard deviations of the sample of these multiplication factors are equal to respectively $m_K = 1.15$ and $s_K = 0.051$. Assuming a normal distribution, the design value of the multiplication factor K_d is determined according to the Bayesian approach:

$$K_d = m_K - t_v s_K \sqrt{1 + \frac{1}{n}} \tag{9}$$

where n is the total number of test results. The value of the coefficient of the Student distribution t_v depends on the value of the product of the weighting factor and the reliability index $\alpha_R \cdot \beta$. In this example with $n = 46$, the coefficient is $t_v = 3.222$, which means that the design value of the correction factor is $K_d = 0.984$. Now the design values referring to all data points i are:

$$R_{d;i} = K_d \cdot R_{\text{pm};i} \tag{10}$$

In this example it is assumed that the characteristic value of the design rule is equal to the value predicted by the proposed model. With use of equation 6 it is now possible to calculate the value of the partial factor. The calibrated value of the partial factor is equal to 1.17.

Instead of assuming a normal distribution it was validated [1] that a Weibull distribution appears to be a better estimation for the strength of adhesive bonded joints. The calculation of the design value is comparable to the procedure for a normal distribution demonstrated above and results into a calibrated value of the partial factor equal to 1.11 [1].

4 Example of the calibration of the conversion factor for ageing effects

In this example a design rule for overlap joints with a polyurethane adhesive is calibrated. The value of the conversion factor for ageing effects is determined by a probabilistic technique, which compares the experimental strength values after ageing with initial values.

Accelerated ageing tests were performed on 25 mm wide single overlap joints with 12 mm overlap length, made of 1 mm thick polyester coated steel sheetings and a cold cured two-component polyurethane adhesive. See figure 7. The specimens were aged under constant conditions. The relative humidity was equal to 95% and to accelerate the ageing process temperatures of 60, 50 and 40 °C were applied. An overview of the failure loads determined after a period of time is given in figure 8. It is noted that only cohesive failure is observed.

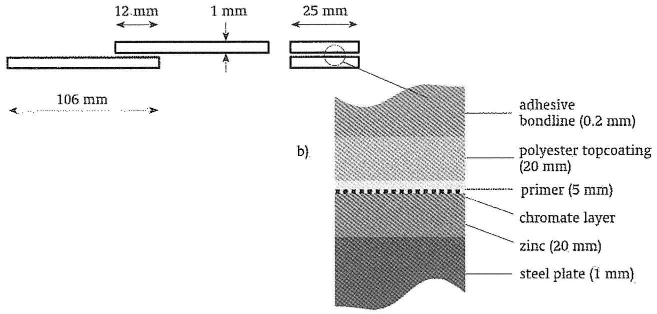

Figure 7. Studied overlap joint: a) geometry, b) cross-section coating

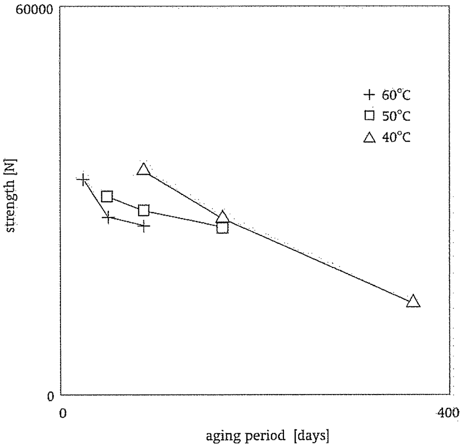

Figure 8. Overview of the mean value of the failure loads under various ageing conditions

To interpret these results with use of statistical techniques, it is necessary to define a relation that gives a proper description of the degradation process. This relation is based on the assumption that water is the main environmental action causing ageing. In general a linear relationship between the amount of water uptake and the magnitude of degradation is assumed [7]. Diffusion models, using exponential relations can predict water uptake. The used semi-empirical relation is described as follows:

- The relation between the resistance R and time t is exponential.
- The resistance of an adhesive bonded at time $t = 0$ is equal to the value R_0.
- After a long period of time the resistance becomes stable and reaches a value R_{inf}.

Based on this, the resistance $R(t)$ can be described as:

$$R(t) = (R_0 - R_{\mathrm{inf}}) \cdot \exp(C_1 \cdot t) + R_{\mathrm{inf}} \tag{11}$$

where C_1 is an empirical constant still to be determined. See also figure 9.

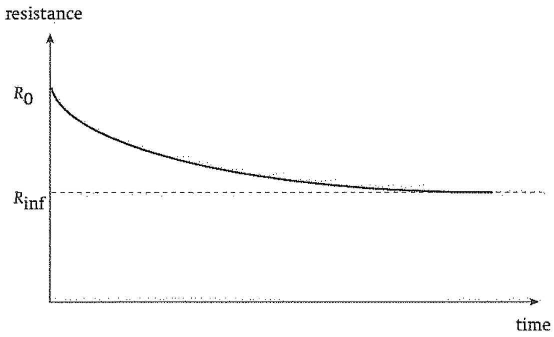

Figure 9. Schematic presentation of equation 11

Many researchers have assumed that accelerated processes can be described by a transformation of time t [8]. If the acceleration is only controlled by temperature the well-known Arrhenius equation might be used. Now the time transformation function $\rho(t,T)$ can be formulated as follows:

$$\rho(t,T) = \exp(C_2 - \frac{C_3}{T}) \cdot t \tag{12}$$

where T is the absolute temperature in Kelvin, while C_2 and C_3 are empirical constants. Combining equations 11 and 12 gives the following general description of the degradation of the resistance as a function of time t and temperature T:

$$R(t,T) = (R_0 - R_{\text{inf}}) \cdot \exp(C_1 \cdot \exp(C_2 - \frac{C_3}{T}) \cdot t) + R_{\text{inf}} \tag{13}$$

To determine the values of the empirical constants of equation 13 on basis of the data set $R_{\text{test};i}(t,T)$ as presented in figure 8, a least squares method is used. The values of R_0, R_{inf}, C_1, C_2 and C_3 that minimize the sum of squares are defined to be the least-squares estimators:

$$\sum_{i=1}^{n_{\text{tot}}} \left(R_{\text{test};i}(t,T) - R(t,T)\right)^2 \tag{14}$$

The results of this statistical evaluation are presented in figure 10. The predicted curve for outside exposures is plotted assuming an average temperature of 10 °C for the whole year. An essential assumption made during the interpretation is that the test results of the specimens, which were not aged ($t = 0$), should not be included in the statistical evaluation. This is, because it is found from various experiments that due to post-curing effects the adhesive behaviour is influenced. In figure 10 also the results of additional specimens exposed outside under Dutch weathering conditions, are plotted. It is observed that the test results of these specimens are on the safe side of the predicted curve. Additional test results of specimens exposed outside are foreseen during the coming years.

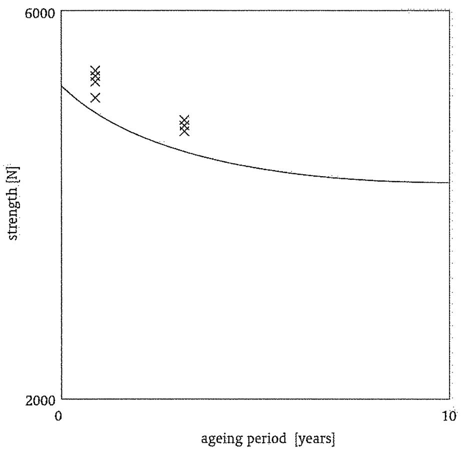

Figure 10. Results of the statistical evaluation of the tests of aged specimens

Based on this interpretation the value of the conversion factor to be used in design rules can be calibrated. The initial value of the strength is equal to $R(t_0) = 5243$ N (without ageing), and the predicted value after a long periods of ageing is equal to $R(t_p) = 4181$ N. According to equation 7 the conversion factor is now equal to 0.76, which means that the strength of the considered joint reduces with 24%. A more advanced alternative to calibrate the conversion factor divides the reference period into a number of periods and makes an evaluation for each period [1]. In this example this results in a conversion factor equal to 0.77 for a reference period of 50 years, which is only a slight difference.

5 Conclusions

A systematic approach to develop design rules for adhesive bonded joints is presented in this article. The principles how to apply structural reliability methods and how to draft prediction models are discussed. Examples of design rules for overlap joints are worked out to illustrate the potential of the approach. Calibration techniques that compare prediction models with test results are applied. Based on these findings, the following conclusions are made:

- To formulate reliable design rules for daily design practice the partial factor approach is the most convenient structural reliability method. The introduction of the conversion factor additional to the partial factor is a practical method to incorporate the effect of the degradation of the resistance in a design rule.
- Besides engineering judgement, probabilistic techniques provide useful information to calibrate the values of the partial factor and conversion factor.
- For adhesive bonded overlap joints there is a good agreement between the proposed prediction model based on the spring model approach and results of tests done for a cold cured two-component epoxy adhesive.
- The example of a single overlap joint made of polyester coated steel sheeting and bonded with

cold cured two-component polyurethane adhesive, indicates that the conversion factor can be calibrated on the basis of accelerated ageing tests.

The presented methodology to develop design rules is straightforward and systematic. Such a systematic approach is a novel method to develop reliable design rules for structural adhesive bonded joints.

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