Computer Aided Design of Bonded Joints

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ABSTRACT. An educational software: *Bonding*, is introduced for the design of bonded joints. *Bonding* is a relatively simple, user-friendly and yet powerful tool for the analysis and design within the emerging arena of bonding. The user starts the application by specifying his case as one of the six available bonding geometries.

In all cases, the user is prompted to describe the *geometry* of the joint, the forces and couples acting on the joint, and to specify the *materials*, i.e., the material used for bonding as well as the base material. The program allows the user to add his own materials and their characteristic.

Invoking next, the *Calculate* command, the software carries out a series of computations, after which it presents a short *report* comprising the *maximum applied stress*, the *minimum required joint dimension*, and whether or not the joint is safe.

1. Introduction

Adhesively-bonded joints are widely used in engineering. Recent years have seen their use increase in structural and safety-critical applications. This increase has been particularly pronounced in the aerospace and automotive industries. The successful use of adhesives in such applications is dependent on a combination of process control and non-destructive testing.

Long term performance of adhesive joints in various environments is the main concern of bonding technology in both military and civil applications. Since joint strength can be greatly degraded by aging, periodic non-destructive strength evaluation of bonded devices is, thus, a critical necessity for quality assurance. The main property of interest is strength.

Adhesive bonding has been used in the furniture industry for a long time. The technique is relatively new however in other industries. The aircraft industry has made considerable inroads, and there are clear signs that the ground passenger vehicles will follow suit soon. The topics of immediate research interest in the area of adhesive bonding seem to be ultrasonic and other non-destructive testing methods, stress intensity factors in the design of bonded joints, analytical and numerical (2 and 3-D FE analysis) modeling, curing and curing temperature, aging of bonds, fatigue degradation and cracking, the effect of immersion (like submersion in marine environment, and in jet fuel), and finally impact. Below we present a glimpse of current research on adhesive bonding.

A method of minimizing the optical distortion from gravity sag on a suspended large autocollimating flat mirror was devised by Robinson [1]. This method consists of an inverted nine-point Hindle-mount. A conventional Hindle-mount is located underneath a skyviewing mirror and is primarily under compression loads from the weight of the mirror. It is not suitable for the situation where the mirror is viewing the ground, since a mirror would tend to fall out of the mount when in an inverted position. The inverted Hindle-Mount design that was adopted by the author consists of bonded joints on the backside of the mirror that allow the mirror to be held or suspended above an object to be viewed. This ability is useful in optical setups such as a calibration test where a flat mirror is located above a telescope so that the telescope may view a known optic.

The objective of a research by Yang [2] was to establish a laser-ultrasound system for NDT (non-destructive testing) evaluation of adhesive bonded joints. In this study, the surface waves were launched thermoelastically to the samples using a Q-switched Nd:YAG pulsed laser. The samples were also tested using surface waves launched by a PZT (piezoelectric) transducer. The experimental data from both tests were then compared to evaluate the benefits or drawbacks of using laser ultrasound. It was found that the laser-induced ultrasound was free of couplant and had good reproducibility and no transmission loss. However, the ultrasound generated by the laser in the thermoelastic regime had low propagating energy and SNR (signal to noise ratio), thus increasing the difficulty of measurement. Several solutions were used in this study to overcome the above-mentioned drawbacks. First, the rise time of the signal was shortened by reducing the radiated spot area of the incident laser beam. Second, an optical slot was added to the original laser system to adjust the geometry of the radiated area of the incident laser beam. The theoretical directivity patterns of the related dimensions of the slots were calculated and compared with the experimental results. The results indicated that it would be possible to adjust the directivity patterns by means of the slot. It was concluded that laser-induced ultrasound with good propagation energy and SNR can be generated and used in NDT applications. Furthermore, adhesive bonded joints indeed can be evaluated using laser-induced ultrasound.

Adams and Drinkwater [3] observed that adhesively-bonded joints are widely used in engineering. Recent years have seen their use increase in structural and safety critical applications. This increase has been particularly pronounced in the aerospace and automotive industries. The successful use of adhesives in such applications is dependent on a combination of process control and non-destructive testing. According to the authors, during the production phase, and also in service with critical structures, non-destructive tests are used to assess the quality and fitness for purpose of products. Non-destructive testing does not measure strength directly, but measures a physical parameter, such as stiffness, which can be correlated to strength. They described typical defects which can occur in adhesive joints and discussed their causes and relative significance. The performance of current physical non-destructive tests was described, and future trends outlined. Particular emphasis was given to ultrasonic and sonic methods as they represent the most common methods of non-destructive testing of adhesive joints.

The influence of adhesive reinforcement on the Mode-I fracture toughness of a double-cantilever beam specimen was investigated by Forte et al [4]. An analytical model based on Reissner's variational theorem, which has previously been shown to accurately predict stress fields and energy release rates for cracked laminates, was used to model the test specimen. A plane-strain model was developed and used to determine the energy release rates for mid-plane cracks in aluminum-adherend bonded specimens with varying amounts of reinforcement in the adhesive. Energy release rates were determined from the present model, which were used to determine fracture toughness for specimens in an experimental program. These compared favorably to results of closed-form analyses from the literature. The amount of reinforcement in the adhesive layer was shown to have a significant effect on the Mode-I adhesive fracture toughness and cracking behavior.

Hahn et al [5] suggested that the diffusion of constituents of solvent-free reactive adhesives into plastic joining parts may exert both negative and positive influences on the properties of adhesive-bonded joints. Procedures in order to prove diffusion processes in the case of adhesive-bonded plastic joints were discussed by the authors, and investigations into the influence of diffusion on joint properties were presented. The results indicated that, because of the mostly short time span until curing, detectable diffusion depths were achieved not so much in the non-cross-linked condition but rather, subject to certain prerequisites, in the cross-linked condition of the adhesives.

Shiloh et al [6] contented that long term performance of adhesive joints in various environments is the main concern of bonding technology in both military and civil applications. Since joint strength can be greatly degraded by aging, periodic non-destructive strength evaluation of bonded devices is, thus, a critical necessity for quality assurance. The authors proposed the application of vibration analysis, concentrating on the damping behavior of the tested object. Contrary to other non-destructive evaluation methods, which indicate only the presence of defects, this method is sensitive mainly to material properties, and hence can assess material degradation. The main property of interest is strength. With this in mind, in stage 1 of the research presented by the authors, it was shown that aging of adhesives and bonded joints can be evaluated non-destructively by vibration analysis, based on the internal friction (damping) effect. Good correlation between the specific damping capacity (SDC) and the shear strength of bonded joints was determined. In stage 2, an additional step towards the target application was achieved, by broadening the range of the tested specimen. Additional adhesives and adherends as well as various geometries and sizes of the bonded joints were tested. The effect of the following factors was established: adhesive aging or shear strength, adherends, temperature, sample size left bracket up to diameter of 356 mm (14 inches) right bracket and sample shapes (flats and rings).

Hadj-Ahmed et al [7] proposed a strength probability law to estimate the shear strength of an adhesive joint. The authors proposed a simplified model that enabled generating an analytical solution of the shear stress present in the adhesive. This strength probability law takes into account the scale effects that are experimentally established for the adhesive joint shear strength, and leads to studying the influence of both adhesive thickness and overlap length on joint strength.

Krasucki and Lenci [8] dealt with the problem of yield design of two bodies, the adherents, joined along their common surface by a thin layer of a third material, the adhesive. Since the computation of the solution of this problem is usually very difficult, a simplified model was developed, which also permitted the qualitative analysis of joint behaviour and determination of its strength. The model was obtained by considering the limit case of adhesive of zero thickness, and the general properties of this limit problem were discussed.

Hahn et al [9] conceded that decisive factors for the successful application of adhesive-bonding technology are an adapted construction method and the possibility of quantitative assessability of the mechanical properties of the component. Adhesive-bonded joints between aluminum sheets and aluminum sections were tested by the authors in the cross-tension/shear-tension test and the deformation-mechanical behaviour of the joints was investigated depending on the loading directions, on the adhesive-layer thickness and on the degree of groove filling. With the aid of a spring-shell adhesive-layer model, it was also possible to develop a calculation concept which is suitable for the component design of larger adhesive-bonded sheet structures. It was shown that the adhesive-layer model can portray the experimentally highlighted connections between the deformation-mechanical behaviour on the one hand and the adhesive-layer thickness and the degree of groove filling on the other hand.

Penado [10] presented a method that facilitates the determination of stress intensity factors in composite bonded joints with interfacial or interlaminar cracks. The method was based on a global/local concept, where the displacements and stresses away from the crack tip are found by a conventional finite element analysis. In the neighborhood of crack tip singularity, where finite element results alone no longer converge, an elasticity solution was constructed using an eigenfunction expansion of the stresses and displacements. It was shown that the method allows accurate determination of stresses and stress intensity factors at the crack tip (within 5% of reference solutions) with a relatively small computational effort by using a coarse FE mesh. In addition, the method did not require special finite elements and can be used with any existing finite element code. Numerical results indicated that, out of various interfacial and interlaminar cracks studied, the largest value of the equivalent intensity factor occurs at the interlaminar crack in the first ply interface of the adherend near the adhesive, but not at the adherend-adhesive interface. These results were consistent with the experimental observation that failure of composite bonded joints typically occurs by delamination of the adherend near, but not at the adhesive.

Lee and Kong [11] developed a criterion for predicting the failure strength of joints bonded by ductile adhesives. To obtain the criterion, first fracture tests were carried out on T-peel joints and single-lap joints with various joint geometries, adhesives, and adhered materials. Then using the fracture loads obtained in the tests, a finite element analysis was performed by which the stresses in the adhesive joints were calculated. It was concluded that the failure of an adhesively bonded joint occurs when the maximum of the ratio of the mean to effective stresses exceeds a certain value, which can be considered a new material constant of a ductile adhesive.

Bogdanovich and Yushanov [12] presented a 3-D variational approach aimed at analyzing crack propagation in adhesively bonded composite joints. The analysis was based on the 3-D mosaic model of a composite body allowing for step-wise material property variations in all three coordinate directions, and variational principle of minimum total potential energy. The displacement field in a composite structure was approximated for all coordinate directions in terms of triple series with Bernstein basis functions. The progressive failure analysis approach utilized critical strain energy release rate criterion to predict various scenarios of the adhesive, cohesive or interlaminar crack propagation. Several cracks of the same type or different types could be analyzed simultaneously. Two numerical examples considered double-lap adhesive bonded joint of unidirectional and cross-ply laminated composites. The results for the `sliding' and `opening' displacements showed that for the bonded joint and loading conditions under consideration, both Mode I and Mode II significantly contributed to the progressive failure process.

Romanos [13] suggested that axisymmetric adhesive joints are increasingly used as alternative means of structural joining particularly in highly loaded power-train components. He discussed the use of high strength single component adhesives which cure anaerobically, and the strength evaluation of joints produced using appropriate industrial assembly techniques.

Wang and Zheng [14] observed that vehicle body structures are conventionally spot-welded together. The technique has a proven track record for its adequacy in body strength and crash-worthiness for automobile applications. Recently, it emerged that tough structural adhesives offer an alternative method of joining with a number of advantages. However, the performance of these adhesives under impact load conditions, representing a possible collision, is not fully understood. The authors reported the modelling of adhesive bonded joints in impact situations using computer based finite element analysis. The key interest was the energy absorption capacity of adhesive bonded structures in comparison to the performance of spot welded joints under identical impact loading conditions. The findings confirmed the viability of such applications for adhesives under impact loads.

Recently, damage to the adhesive layer has been investigated by in-situ observation under several load conditions, according to Imanaka et al [15]. The authors maintained however, that these observation have been limited to the surface of the adhesive layer. If an adhesively bonded butt joint with a very thin adhesive layer could be tested, damage to the interior of the adhesive layer could be observed under transmitted light, which would facilitate clarification of the fracture mechanism of adhesively bonded joints. To observe the damage interior to the adhesive layer, the authors made adhesively bonded butt joint specimens using 0.3 mm-thick steel plates with plasticizer and rubber modified epoxy adhesives. Then, cyclic tensile fatigue tests were conducted using these joints, where damage to the adhesive layer was observed by a microscopic video-camera under transmitted light. The main results were as follows: In the case of a butt joint with plasticizer-modified adhesive, an initial crack appeared at the end of the adhesive/adherend interface. On the other hand, in the case of a butt joint with rubber-modified adhesive, the damage zone appeared in the middle of the adhesive layer. These observations were discussed from the viewpoint of stress and strain distributions of the adhesive layer.

Based on the development of a metro car body, it was described by Starlinger and Koch [16] how a hybrid modular construction was implemented by the use of sandwich type large components in combination with large aluminium structural components. They reported that the modular design achieved a substantial reduction of the total manufacturing costs. The new hybrid form of construction called for the use of new cold joining techniques in the form of bolted systems and flexible bonded joints as structural joining elements. However, the prerequisite for the development of hybrid car bodies was a long-term intensive co-operation between the vehicle manufacturer and the adhesive supplier. For structural optimizing, special modelling strategies were derived by the finite-element method. Static testing of the prototype car body structure at different coupling pressures and with various vertical loading patterns confirmed that the models developed are suitable for the intended purpose. In addition, a fatigue test with 10 million load cycles confirmed the fitness of the hybrid car body system for typical metro applications.

Techniques for joining of pultruded composite profiles for bridge-deck applications were designed and analyzed by Zetterberg et al [17]. It was shown that both adhesively bonded and bolted joints can be designed to fulfill stringent requirements, but it became clear that the former was the preferred alternative. Methodology was described for analyzing a large composite structure composed of modular construction elements and to determine the load transfer between composite profiles.

The effect that test environment and pre-conditioning has on the fatigue behaviour of CFRP/epoxy lap-strap joints was investigated by Ashcroft et al [18]. It was shown that the fatigue resistance of the lap-strap joints did not vary significantly until the glass transition temperature was approached, at which point a considerable reduction in the fatigue threshold load was observed. It was also noted that absorbed moisture resulted in a significant reduction in the glass transition temperature of the adhesive. This must be taken into account when selecting an adhesive to operate at elevated temperatures. The locus of failure of the joints was seen to be highly temperature dependent, transferring from primarily in the composite adherend at low temperatures to primarily in the adhesive at elevated temperatures. It was also seen that as the crack propagated along the lap-strap joint, the resolution of the forces at the crack tip tended to drive it into the strap adherend, which could result in complex mixed mode fracture surfaces.

Kwon and Lee [19] observed that surface roughness of adherends greatly affects the strength of adhesively bonded joints. They investigated the effect of surface roughness on the fatigue life of adhesively bonded tubular single lap joints, analytically and experimentally by a fatigue torsion test. The stiffness of the interfacial layer between the adherends and the adhesive was modelled as a normal statistical distribution function of the surface roughness of the adherends. From the investigation, it was found that the optimum surface roughness of the adherends for the fatigue strength of tubular single lap joints was dependent on the bond thickness and applied load.

Imanaka et al [20] suggested that most adhesively bonded joints are under complicated distributed triaxial stress in the adhesive layer. For estimating of strength of adhesively bonded joints, it is crucial to clarify behavior of yield and failure of the adhesives layer under triaxial stress conditions, the authors contended. Two types of the adhesively bonded joints were used by them: One is the scarf joint which is under considerably uniform normal and shear stresses in the adhesive layer, where their combination ratio can be varied with scarf angle. The other is the butt joint with thin wall tube in which considerably uniform pure shear can be realized in the adhesive layer under torsional load conditions. These joints can cover the stress triaxiality in adhesive layers of most joints in industrial application. The effect of stress triaxiality on the yield and fracture stresses in the adhesive layer were investigated using the joints bonded by three kinds of adhesives in heterogeneous and homogeneous systems. The results showed that both the yield and failure criterion depended on the stress triaxiality and that the fracture mechanism of the homogeneous adhesive was different from that of the heterogeneous one. From these experimental results, a method of estimating the yield and failure stresses was proposed in terms of a stress triaxiality parameter.

The influence of moulding temperature on the peel strength of a bonded joint was investigated by Fernando et al [21] for a sulphur cured semi-EV natural rubber vulcanisate. A higher peel force was recorded at the higher moulding temperature. The effect of vulcanization temperature on peel strength was thought to arise from a change in the physical properties of the rubber and modifications of the rubber near the bonded interface as a result of active species migration during vulcanization. A series of parallel investigations were conducted to find supporting evidence for these findings. From these studies it was concluded that it is a combination of changes in the mechanical properties of the natural rubber vulcanisate and any changes induced by the migration mechanisms that determines the final strength of the bonded assembly.

A study was carried out by Tay and associates [22] to investigate the use of induction heating for rapid curing of a commercially available room-temperature curing paste adhesive. It was shown that induction heating can be successfully used to cure a room-temperature curing paste adhesive. Further, results of single lap shear and double notched shear specimen tests showed no substantial reduction in the strength of bonded joints with the use of embedded susceptors.

Jensen et al [23] noted that there are instances where efficiency and safety may be compromised as a result of deteriorating fluid transport systems. Thus, it is worth evaluating other methods that can repair the damage for a temporary period without shutting down the operation. The authors conducted a study to evaluate the durability of an epoxy-bonded steel in aqueous environments that would represent such a repair. EPON 828 was chosen as the epoxy resin, and dicyandiamide and polyamidoamine were two types of curing agents evaluated in this study. The epoxy-bonded steel joints were exposed in either distilled water or 3.4% NaCl solution for various times. The mechanical strength of the bonded joints was evaluated using a three-point flexure test. The interfacial shear strength of unaged samples ranged from 0.93 to 0.32 MPa. It was found that the interfacial shear strength decreased with aging time for both epoxy-bonded systems. Scanning electron microscopy (SEM), optical microscopy, and X-ray photoelectron spectroscopy (XPS) were used to determine the locus of failure of the bonded joints. It was concluded that failure occurred cohesively within the oxide layer if oxides were present on the substrate surface prior to the bonding procedure.

Applications for structural adhesives in a marine environment will generally involve much thicker adherends than used in some other industries, according to Knox and Cowling [24]. The effect of aging on adhesively bonded joints in a wet environment is particularly important for marine applications. A major concern is the sensitivity of the adhesive to the effects of water. The durability performance of thick-adherend steel lap joints and the bulk adhesive were investigated by the authors by using accelerated aging techniques (30 degree C, 100% relative humidity). Various simple geometric factors were shown to affect joint performance. The removal of the spew fillet, the application of a stress and the joint orientation would all significantly influence durability performance. It was found that water affects both the adhesive and the adhesive/adherend interfacial zone.

The aging in water of steel/composite glass polyester specimens bonded with an epoxy adhesive was studied at 25 degree and 40 degree C by Roy et al [25]. The damage processes were found to be controlled by water diffusion. The main damage was due to the adhesive swelling but, when specimens were loaded during immersion, the stress gradient at the extremities of the joint accelerated the water diffusion and then the failure of specimens. A simple logarithmic relationship was found to exist between the specimen life time and the applied load.

A sealant made from a stoichiometric mixture of amine terminated butadiene-acrylonitrile copolymer and epoxide resin was used by Comyn et al [26] to make single lap-joints in aluminum. These were immersed in jet-fuel, water, antifreeze and an antifreeze-water mixture prior to testing. Strengths were much increased by pre-treating the metal by phosphoric acid anodization or with silane coupling agents. Joints were weakened in antifreeze but not in jet-fuel or antifreeze-water. In water weakening of joints with the salines was accompanied by corrosion.

Below we present the *Bonding* software, where a number different bonding geometries are treated under typical loading conditions. *Bonding* is part of a larger educational software package (Bogis, et. al., 2000, 2000a, 2002, 2002a) that is being developed by the authors.

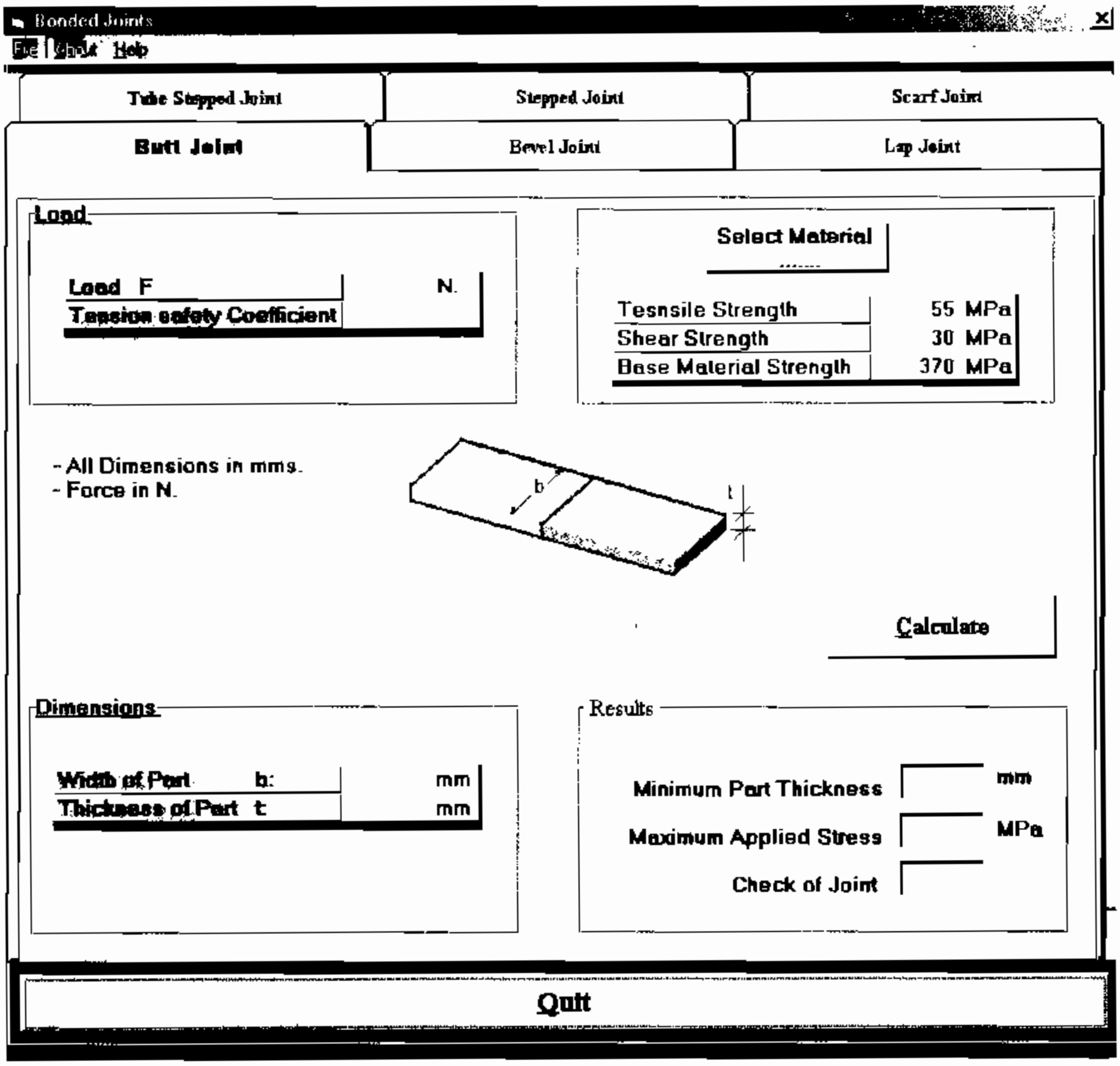
2. The Bonding Package

The software is accessed by clicking on the *Bonding* button of Fig. (1) on the main menu of *Fasteners*. As soon as the mouse contacts this button, the display of Fig. (1a) becomes visible.

Fig. (1) : The icon for Bonding.

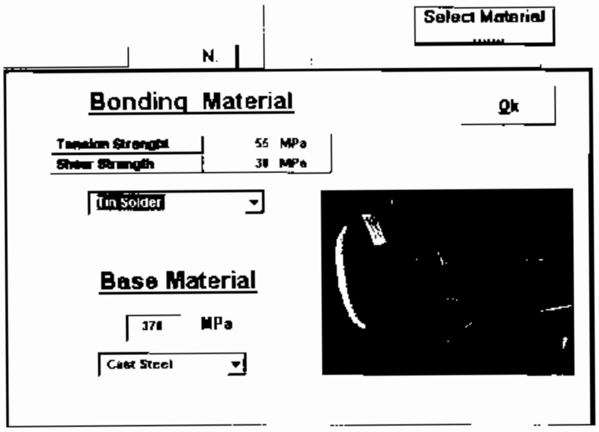
Fig. (1a) : The symbol for bonding.

Invoking the *Bonding* button causes the main menu of Fig. (2) to be displayed. Lined horizontally at the top of the main screen are the six prompts for the types of bonded joints, with *Butt Joint* being selected in the figure. The user is prompted to specifify the tensile load and its safety coefficient, to select materials for the elements of the joint (Fig. 2, 2a and 2b), and to specify dimensions. Note that the user is given the freedom to add new joining compounds and new base materials. Pressing of the *Calculate* button initiates the computations. The results are displayed in the lower right corner of the same menu (Fig. 2). Clicking on the horizontal bar button at the bottom terminates operations and exits *Bonding*.



Tesnsile Strength 55 MPa
Shear Strength 30 MPa
Base Material Strength 370 MPa

Fig. (2) : The main screen of Bonding.



Tension Strength 55 MPa
Shear Strength 30 MPa
Tin Solder
370 MPa
Cast Steel

Fig. (2a) : Selection of materials for bonding.

Figure (3) shows the menu for a *Bevel* Joint, and Fig. (4) for a *Lap* joint. The manus for the rest of the six joints are presented in Figs. (5) to (7)

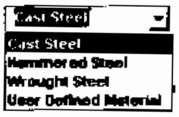
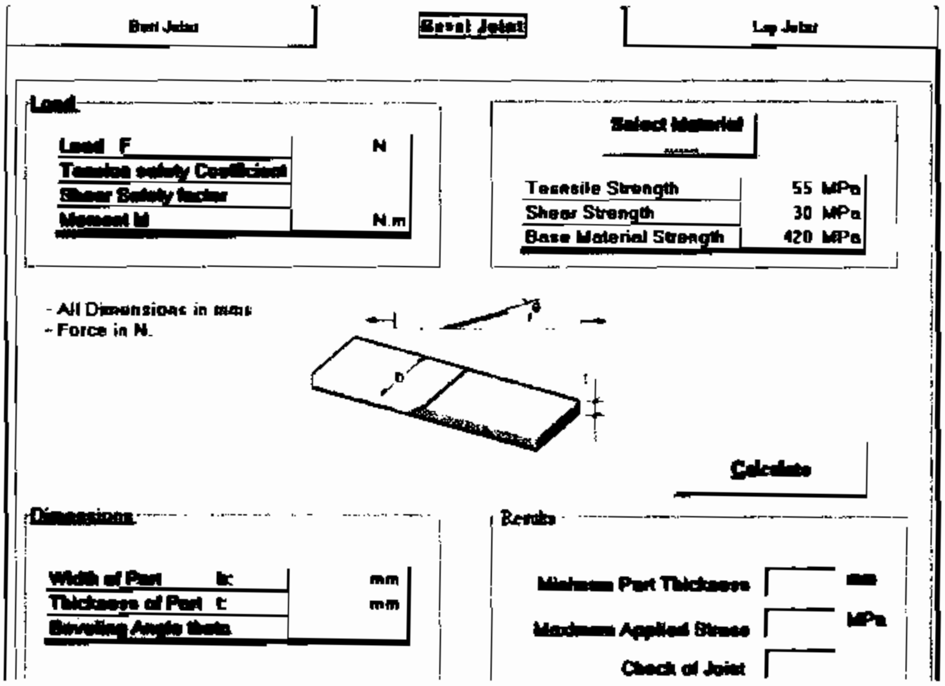
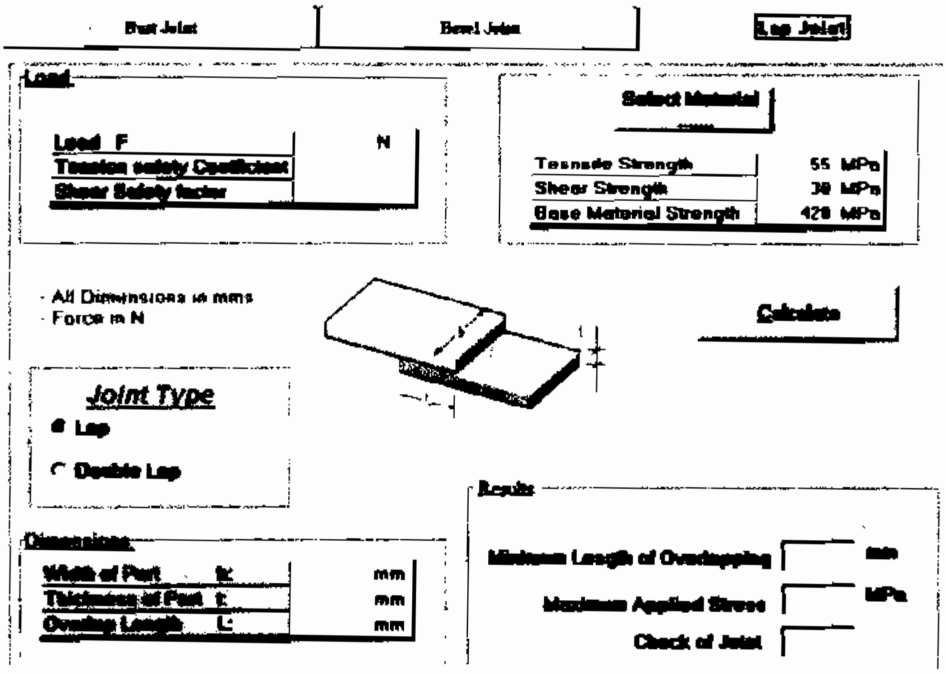


Fig. (2h) : Specification of the base material.



Tensile Strength 55 MPa
Shear Strength 30 MPa
Base Material Strength 420 MPa

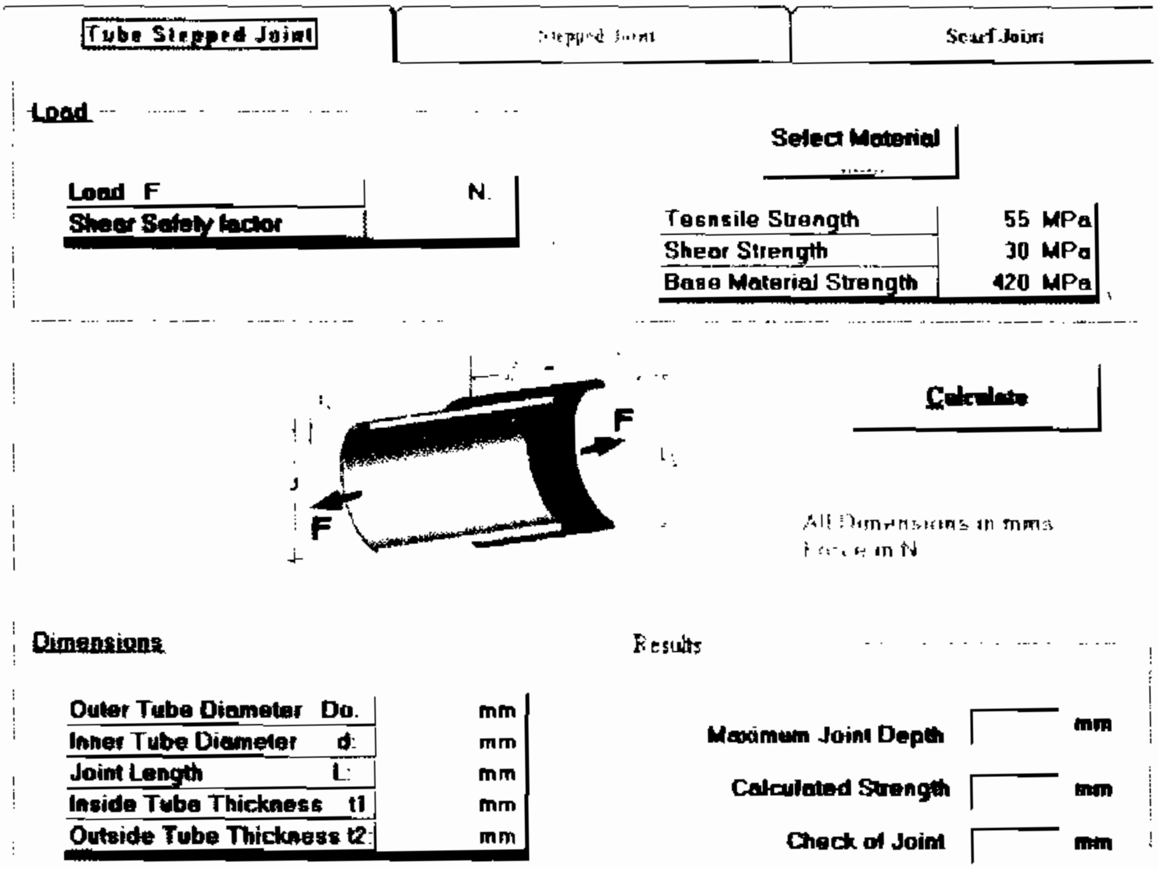
Fig. (3) : The menu for a bevel joint.



Tensile Strength 55 MPa
Shear Strength 30 MPa
Base Material Strength 420 MPa

● Lap
○ Double Lap

Fig. (4) : The menu for a lap joint.



Load

Load F		N.
Shear Safety factor		

Tesnsile Strength	55 MPa
Shear Strength	30 MPa
Base Material Strength	420 MPa

All Dimensions in mms
Force in N

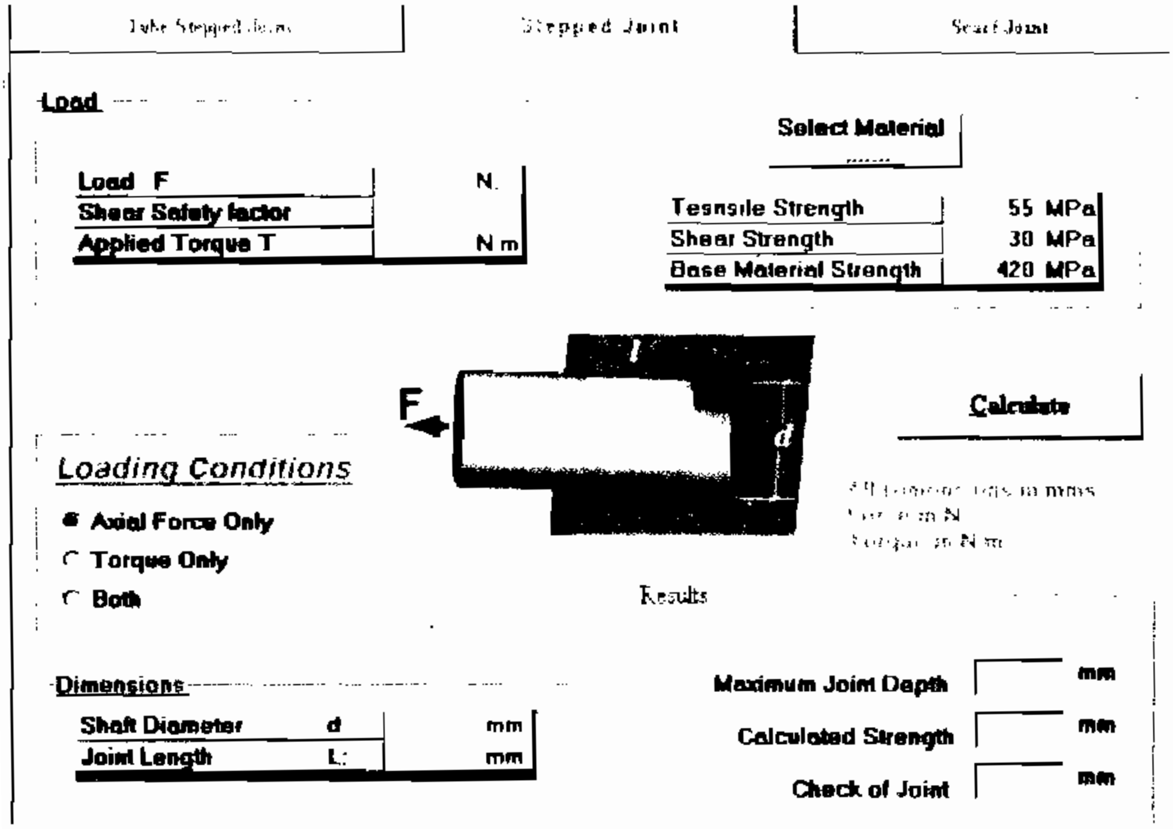
Dimensions

Outer Tube Diameter Do.		mm
Inner Tube Diameter d:		mm
Joint Length L:		mm
Inside Tube Thickness t1		mm
Outside Tube Thickness t2:		mm

Results

Maximum Joint Depth		mm
Calculated Strength		mm
Check of Joint		mm

Fig. (5) : The menu for a tube stepped joint.



Load

Load F		N.
Shear Safety factor		
Applied Torque T		N m

Tesnsile Strength	55 MPa
Shear Strength	30 MPa
Base Material Strength	420 MPa

All Dimensions in mms
Force in N
Torque in N m

Loading Conditions

● Axial Force Only
○ Torque Only
○ Both

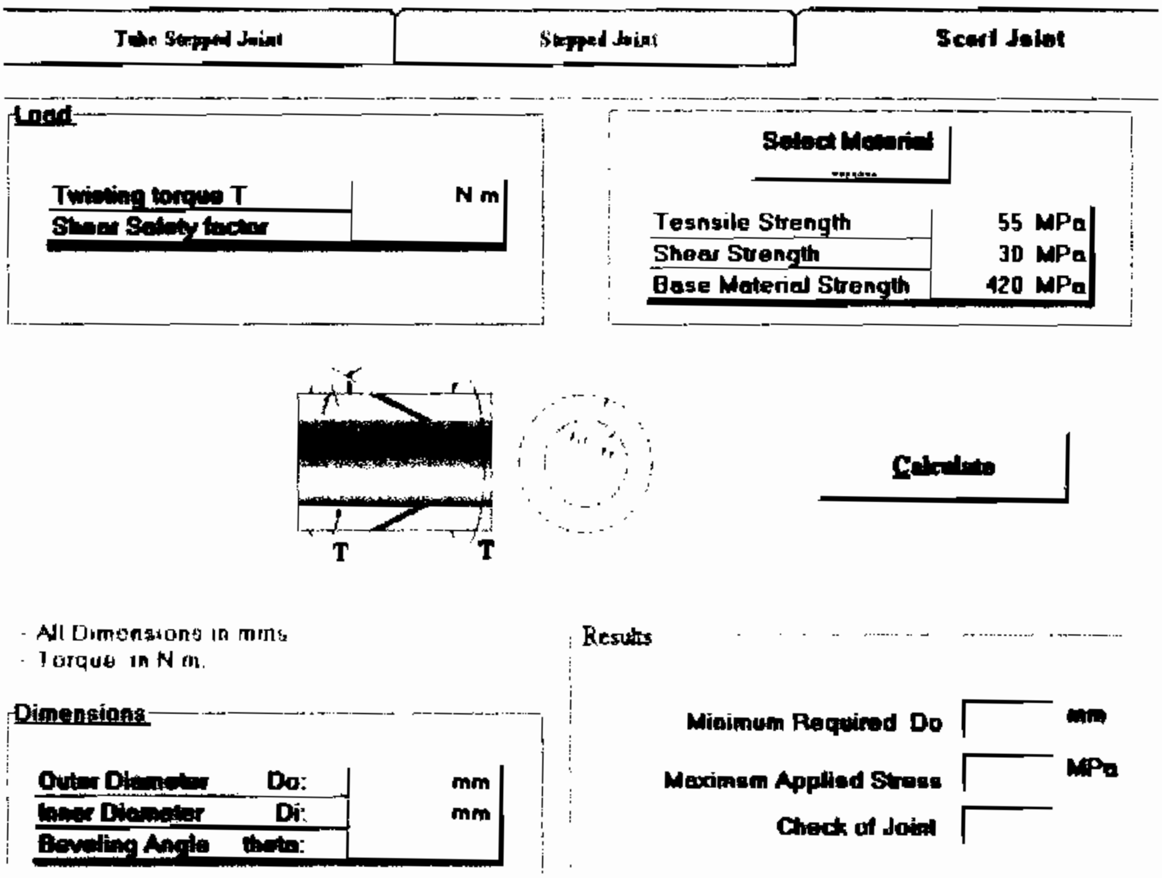
Results

Dimensions

Shaft Diameter d		mm
Joint Length L:		mm

Maximum Joint Depth		mm
Calculated Strength		mm
Check of Joint		mm

Fig. (6) : The menu for a stepped joint.



Tesnsile Strength 55 MPa
Shear Strength 30 MPa
Base Material Strength 420 MPa

Fig. (7) : The menu for a scarf joint.

3. Concluding Remarks

Bonding is a relatively simple, user-friendly and yet powerful tool for the analysis and design within the emerging arena of bonding.. The user starts the application by specifying his case as one of the six available bonding geometries.

In all cases the user is prompted to describe the *geometry* of the joint, the forces and couples acting on the joint, and to specify the *materials*, i.e., the material used for bonding as well as the base material. The program allows the user to add his own materials and their characteristics.

Invoking next the *Calculate* command, the software carries out a series of computations, after which it presents a short *Report* comprising the *maximum applied stress*, the *minimum required joint dimension*, and whether or not the joint is safe.

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استخدام الحاسوب في تصميم وصلات المواد اللاصقة

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المستخلص. برنامج تعليمي لتصميم الوصلات الميكانيكية التي تستخدم فيها المواد اللاصقة. البرنامج مع كونه بسيطا وسهلا في الاستخدام، إلا أنه أداة قوية في هذا المجال، إذ إن مستخدمه يبدأ بتوصيف حالته من بين ستة تصاميم هندسية. وفي جميع الحالات فإنه يطالب بإدخال بيانات مبسطة لتوصيف أبعاد الوصلة، وكذلك اختيار مادتي الوصلة ومادة الربط المستخدمة في بنائها والأحمال الواقعة عليها من قوة أو عزم. كما أن البرنامج يمكن المستخدم من إدخال بيانات المواد الخاصة به وسماتها.

بعدها يوفر البرنامج للمستخدم إجراء التحليل لهذه الوصلة، والتي يقوم البرنامج بتقديم تقرير مختصر عنها يوضح فيه أقصى إجهاد ناتج عن الحمل المؤثر، وكذا أفضل الأبعاد الهندسية لها، وإذا ما كانت الإجهادات في الوصلة تحت التصميم آمنة من عدمه.