A Study on Stress Analyses and Strength Evaluation for Adhesive Joints Subjected to Static and Impact Loadings

(静的及び衝撃的荷重を受ける接着維手の応力解析及び強度評価に関する研究)

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Adhesive joints have been used widely in automobile, aerospace, electric industry as the adhesives are enhanced. However, the interface stress distributions which govern the joint strength for several types of adhesive joints have not been fully elucidated. Thus, it is necessary to establish a reasonable design method for adhesive joints taking the interface stress distributions of the joints into account. In the present study, the interface stress distributions are examined taking into account the effects of some influential factors, such as Young’s modulus, dimensions and etc., on the interface stress distributions and the joint strength for epoxy-steel composite cylinders, single-lap adhesive joint with similar and dissimilar adherends and bonded shrink-fitted joint, subjected to static and impact loadings for establishing design methods and improving the joint strengths. The contents of the present study consist of eight chapters described below.

In Chap. 1 [Introduction], the previous researches have been overviewed and then the issues to be studied are described. The issues to be studied are i) to examined the interface stress distributions of the joint in detail taking into account of the stress singularity, ii) to establish a method for predicting the joint strength, iii) to examine the characteristics of the joints subjected to impact loadings as well as static loadings. The objective of the present study is to examine the interface stress distributions (singular stresses) of epoxy-steel composite cylinders, single-lap adhesive joint and bonded shrink-fitted joint subjected to static and impact loadings using axi-symmetrical theory of elasticity, FEM and experiments, and to predict the joint strengths using the obtained interface stress distributions for better designing the adhesive joints.

In Chap. 2 [Axi-symmetric Stress Analysis and Strength Evaluation of Epoxy-Steel Composite Cylinders Subjected to Static Push-off Loadings], a method for analyzing the interface stress distributions in epoxy-steel composite cylinders subjected to static push-off loadings is demonstrated using axi-symmetrical theory of elasticity. In the theoretical analysis, the effects of Young’s modulus of the hollow cylinder (epoxy) $E_2$ and the diameter of the solid cylinder (steel) $2b_1$ on the interface stress distribution are examined. In addition, the effects of the diameter of the support hollow cylinder $2a_2$ and the stress distribution due to the applied push-off loadings $2a_0$ are also examined. It is found that the normal stress at the interfaces increases as the values of $E_1/E_2$ and $b_1/a_0$ decreases, and the values of $b_1/b_2$ and $a_2/b_1$ increase. The shear stress at the lower interface edge increases as the value of $a_2/b_1$ increase; while it decreases as the values of $E_1/E_2$, $b_1/b_2$ and $b_1/a_0$ increases in the theoretical analysis. Then, based on the normal stress and the shear stress obtained from the theoretical analysis, it is found that the push-off strength increases as i) $E_1/E_2$ increases, ii) $b_1/b_2$ increases, iii) $a_2/b_1$ decreases, iv) $b_1/a_0$ increases. A valid method for estimating the singularity is proposed and the discussion is made. It is seen that the rupture of the epoxy-steel composite cylinders initiates from the lower interface edge when the push-off load is applied to the upper end of solid cylinder. Using the interfaces stresses obtained from the theoretical analysis and analogous tests, the joint strength of epoxy-steel composite cylinders is estimated. The comparison between the present theoretical method and the shear lag theory is
also made. It is found that the singular stress must be taken into account in evaluating the strength. For verification of the present analysis of the interface stress distributions, finite-element method (FEM) is also carried out. A fairly good agreement is observed among the analytical, experimental and FEM results. Finally, the optimal value of the light weight of the epoxy-steel composite cylinders is discussed using the specific strength examination, and as an example, it is demonstrated that the reduction in weight is by 48.1% in this research.

In Chap. 3 [Axisymmetric Stress Analysis and Strength Evaluation of Epoxy-Steel Composite Cylinders Subjected to Static Torsional Loadings], the interface stress distributions in epoxy-steel composite cylinders subjected to static torsional loadings are analyzed using axi-symmetrical theory of elasticity. In the theoretical analysis, the effects of Young’s modulus of the hollow cylinder (epoxy) $E_2$ and the diameter of the solid cylinder (steel) $2b_1$ on the interface stress distribution are examined. It is observed that the shear stress at the upper interface edge in the epoxy-steel composite cylinders subjected to torsional loadings decreases as the ratios $E_1/E_2$ and $b_1/b_2$ increase in the theoretical analysis. Thus, it is observed that the torsional strength is improved, as i) $E_1/E_2$ increases, ii) $b_1/b_2$ increases. Then, a valid method for estimating the singularity is proposed and the discussion is made. It is seen that the rupture initiates near the upper interface edges. Using the interfaces stresses obtained from the analytical analysis and analogous tests, the joint strength of epoxy-steel composite cylinders is estimated. For verification of the present analysis of the interface stress distributions, finite-element method (FEM) is also carried out. A fairly good agreement is seen among the analytical, experimental and FEM results.

In Chap. 4 [FEM Stress Analysis and Strength Evaluation of Single-lap Adhesive Joints Subjected to Impact Tensile Loadings (with similar adherends)], the stress wave propagations and interface stress distributions in the single-lap adhesive joint subjected to impact tensile loadings are analyzed using the three-dimensional finite element method (3D-FEM) taking into account the strain rate sensitive of the adhesive in elasto-plastic deformation ranges. In the FEM calculations, the effects of Young’s modulus of the adherend $E_1$, the overlap length $2L_2$ and the thickness $2t_2$ of the adhesive layer and the initial impact velocity of the dropping weight-hammer $V$ on the stress wave propagations and the interface stress distributions are examined. It can be seen that the maximum principal stress $\sigma_1$ of the single-lap adhesive joint subjected to impact tensile loadings increases as i) Young’s modulus of the adherend [I] $E_1$ increases, ii) the overlap length $2L_2$ decreases, iii) the thickness of the adhesive layer [II] $2t_2$ decreases, iv) the initial impact velocity of the dropping weight-hammer $V$ increases. Then, based on the stress wave propagations and interface stress distributions, it can be concluded that the strength of the single-lap adhesive joint subjected to impact tensile loadings increases as i) Young’s modulus of the adherend [I] $E_1$ decreases, ii) the overlap length $2L_2$ increases, iii) the thickness of the adhesive layer [II] $2t_2$ increases. Different characteristics of the joints are shown between the different loading types of static and impact. In the case of the static tensile loadings, the maximum principal stress of the joint increases as i) Young’s modulus of the adherend [I] $E_1$ decreases, ii) the overlap length $2L_2$ decreases, iii) the thickness of the adhesive layer [II] $2t_2$ increases. In addition, experiments are carried out to measure the strain responses and to predict the strength of the joint subjected to impact tensile loadings. Furthermore, comparisons of the strain responses between the numerical results and the experimental results are made. A fairly good agreement is shown between the FEM and experimental results. A method for increasing the joint strength is proposed. The strength of the single-lap adhesive joint subjected to impact tensile loadings is estimated experimentally and it is obtained between 5.439 J and 5.620 J in the present study.

In Chap. 5 [FEM Stress Analysis and Strength Evaluation of Single-lap Adhesive Joints Subjected to Impact Tensile Loadings (with dissimilar adherends)], the stress wave propagations and interface stress distributions in the single-lap adhesive joint with dissimilar adherends subjected to impact tensile loadings are
analyzed using the three-dimensional finite element method (3D-FEM) taking into account the strain rate sensitive of the adhesive in elasto-plastic deformation ranges. In the FEM calculations, the effects of Young’s modulus of the dissimilar adherends (\(E_1\) & \(E_3\)), the overlap length \(2l_2\) and the thickness \(2t_2\) of the adhesive layer and the initial impact velocity of the dropping weight-hammer \(V\) on the stress wave propagations and the interface stress distributions are examined. It is seen that the maximum principal stress \(\sigma_1\) of the single-lap adhesive joint with dissimilar adherends (aluminum - steel) subjected to impact tensile loadings increases as i) the difference between Young’s modulus of the adherend \(E_1\) and Young’s modulus of the adherend \(E_3\) increases, ii) the overlap length \(2l_2\) decreases, iii) the thickness of the adhesive layer \(2t_2\) decreases, iv) the initial impact velocity of the dropping weight-hammer \(V\) increases. Then, from the obtained stress wave propagations and interface stress distributions, it can be concluded that the strength of the single-lap adhesive joint with dissimilar adherends (aluminum - steel) subjected to impact tensile loadings increases as i) Young’s modulus of the adherend \(E_1\) approaches Young’s modulus of the adherend \(E_3\), ii) the overlap length \(2l_2\) increases, iii) the thickness of the adhesive layer \(2t_2\) increases. In addition, it is found that the strength of the joint with dissimilar adherends is smaller than that of the joint with similar adherends. Furthermore, is is observed that the rupture initiates at the interface edge of the adherend with higher Young’s modulus (steel). Moreover, the characteristics of the single-lap adhesive joint with dissimilar adherends under impact loadings are shown to be so different from those of the joint under static loadings, and then it is seen that the rupture initiates at the interface of the adherend with smaller Young’s modulus (aluminum) in the joint under static tensile loadings. Finally, experiments are carried out to measure the strain responses and to predict the strength of the joint subjected to impact tensile loadings. A fairly good agreement is seen between the FEM and experimental results concerning the strain responses. The strength of single-lap adhesive joint with dissimilar adherends (aluminum - steel) subjected to impact tensile loadings is estimated experimentally and it is obtained over 5.98 J in the present study.

In Chap. 6 [FEM Stress Analysis and Rupture Prediction of Bonded Shrink-Fitted Joints Subjected to Impact Push-off Loadings], the rupture position and the strength of the bonded shrink-fitted joint subjected to impact push-off loadings taking into account the adhesive plastic deformation with high strain rate are estimated in elasto-plastic deformation ranges using FEM and experiments. In the FEM, the stress wave propagations and stress distributions in the bonded shrink-fitted joint are examined. The effects of Young’ modulus of the shaft and the ring \(E_1(=E_3)\), the diameter of the shaft \(2h_1\), the engaged height of the adhesive \(2h_2\) and the interference \(\delta\) on the stress wave propagations are also examined. It is seen that the equivalent von Mises stress \(\sigma_{eq}\) in the adhesive layer at the upper interface of the bonded shrink-fitted joint subjected to impact push-off loadings increases as i) Young’s modulus ratio \(E_1/E_2\) decreases, ii) diameter ratio \(b_1/b_2\) decreases, iii) height ratio \(h_1/h_2\) increases, iv) interference \(\delta\) decreases. From the stress wave propagations obtained from the present FEM calculations, it can be predicted that the strength of bonded shrink-fitted joint subjected to impact push-off loadings increases under the following conditions: i) as Young’s modulus ratio \(E_1/E_2\) increases, ii) as the diameter of the shaft \(2b_1\) increases, ii) as the bonded engaged height \(2h_2\) (the adhesive layer’s height) increases, iii) as the interference \(\delta\) increases. In addition, it is observed that the rupture initiates in the adhesive layer at the upper interface of the joint subjected to impact push-off loadings. Furthermore, the characteristics of the joint under impact push-off loadings are compared with those of the joint under static push-off loadings. As the results, it is found that the characteristics are so different. Moreover, the strain responses obtained from the FEM calculations are compared with those obtained from the experiments. A fairly good agreement is found between the FEM and experimental results concerning the strain responses. Finally, the joint strength is evaluated in the experiments. In the evaluations, the relative slip between the shaft and the ring is
examined describing as impact energy $IE$. As the results, the obtained $IE$ is about 20.85 J in the present study.

In Chap. 7 [Guideline for Designing The Adhesive Joints Subjected to Static and Impact Loadings], the mechanical properties of epoxy-steel composite cylinders, single-lap adhesive joint and bonded shrink fitted joint subjected to static and impact loadings are summarized to provide the guideline for designing the adhesive joints in details for each adhesive joints subjected to different external loadings (static & impact) from the reliable standpoint.

In Chap. 8 [Conclusions], the conclusions are described for each adhesive joint subjected to some types of external loadings based on the results obtained from theoretical analysis, FEM calculations and experiments. Main results obtained are as follows, i) interface stress distributions are examined for epoxy-steel composite cylinders, single-lap adhesive joint with similar and dissimilar adherends and bonded shrink-fitted joint, ii) singular stress occurs at the interface edges in the adhesive joints, iii) for the epoxy-steel composite cylinders, the difference on the interface stress distributions is substantial between the analytical and the shear lag model, iv) it is found that the characteristics of the joints under impact loadings are so different from those of the joint under static loadings, v) thus, it is noticed that in designing the adhesive joint, the difference of the loading types must be taking into account. Furthermore, the outlook which concerning the necessary research issues in the future are described briefly.