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学 位 論 文 要 旨
Dissertation Summary

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論　文　名: CHARACTERIZATION OF MICROSCOPIC IMPACT DAMAGE IN CFRP LAMINATES WITH TOUGHENED INTERLAYERS
(Dissertation Title)

This study aims at characterization of microscopic impact damage of CFRP laminates with toughened interlayers. In general, CFRP has been applied to various engineering application due to its superior properties such as high stiffness and strength. For example, CFRP is employed in aircraft structure such as wings, turbo-fan engines and a fuselage. Nonetheless, it is still vulnerable to damage induced by low-velocity and high-velocity impact. The damage due to low-velocity impact can be classified either barely visible impact damage (BVID) or clearly visible impact damage (CVID). In the former case, even though a small dent is created on the laminate surface, significant damage including matrix cracking and delamination is often generated inside the laminate.

On the contrary, high-velocity impact creates clear evidence such as a crater on the surface besides more catastrophic failure than low-velocity impact. In the event of high velocity impact, punching failure, fibre failure, matrix cracking and delamination are considered as main damage mechanism that occurred in composite materials. In general, it is supposed that punching failure is initially generated and followed by fibre breakage before delamination occurs at the back side interfaces of the laminate. The relative thickness of each damage process

depends on overall laminate thickness.

Accordingly, CFRP laminates toughened with interlayers have been developed to improve interlaminar fracture toughness to constrain initiation and propagation of delamination. Thus far, only a few study has been carried out regarding comparison of microscopic damage in CFRP laminates toughened with interlayers between low- and high-velocity impacts. Furthermore, to the author knowledge, no numerical model has been developed to reproduce the impact damage processes in this type of laminate. Therefore, this study aims to thoroughly characterize and model the microscopic damage of CFRP with toughened interlayers subjected to both low- and high-velocity impacts through experiment characterization and numerical modelling.

The material used in this study was T800S/3900-2B (Toray Industries Inc.), CFRP laminates toughened with interlayers, employed in aircraft structure (B787). The fiber strength of this material is about 10% higher than that of T800H/#3900-2 used in B777 aircraft. The stacking sequence was cross-ply lamination $[0^0/90^0]_{2S}$. First, low-velocity impact testing was performed by using a drop-weight apparatus developed in the laboratory. Meanwhile, high-velocity impact testing was carried out using a ballistic impact testing machine. The damage observed in the experiment was then reproduced via numerical modelling using commercial finite element analysis (FEA) software (ABAQUS/Explicit). In addition, a user subroutine program (VUMAT) was also incorporated in the FEA software for failure modelling. The laminate consisting of the base ply and the interlayer was modelled as elastic solid elements, whereas the impactor was modelled as a rigid body. The delamination was considered by introducing cohesive elements which were inserted not only within the base ply, but also between the base ply and the interlayer to reproduce both intralaminar and interlaminar delaminations.

It is found from the experiment results that the splitting cracks on the front surface of the laminate propagate in the fiber direction in the high-velocity impact. In contrast, in the low-velocity impact, the cracks normal to the fiber direction are generated on the front surface. The cracks on the front surface are generated due to high compressive stress in the fiber direction (0^o-direction) during the impact. The degree of damage is relatively large in the high-velocity impact even though the deformation is localized. In contrast, in the low-velocity impact, the damage is relatively mild because the ratio of dissipated energy to incident impact energy is larger than that in the high-velocity impact.

In addition, the interlaminar delamination tends to propagate in the fiber direction for both impacts, resulting in a galaxy shape delamination. It is also interesting to note that not only the interlaminar but the intralaminar delaminations are generated inside the laminate. With regard to the role of toughened interlayers, the interlayers suppress the delamination when the incident impact energy is smaller than the threshold value (approximately 0.18 J). Furthermore, the high fracture toughness of the interlayers sometimes produces the transition of interlaminar delamination to intralaminar delamination.

Apart from experimental characterization, numerical modelling was also successfully developed. The comparison between experiment and numerical modelling indicates that the present numerical modelling can reproduce the damage pattern including intralaminar delamination. The simulation considering both interlaminar and intralaminar delaminations gives better agreement with the experiment result of the deflection rate in the deflection-time curve.

In conclusion, the novel finding in this research is the generation of intralaminar delamination in this type of laminate which is never observed in conventional CFRP laminates. Furthermore, the simulation with cohesive elements which express both intralaminar and interlaminar delaminations provides better result than the simulation with cohesive elements for interlaminar delamination only.