EFFECTS OF COVER PLATE STIFFNESS ON ULTIMATE STRENGTH OF BEARING-TYPE MULTI-ROW BOLTED CONNECTIONS FOR FRP COMPOSITE STRUCTURES

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1. INTRODUCTION

In recent years, fiber reinforced polymer (FRP) composites have been introduced in civil engineering industries due to its excellent material properties such as high strength-to-weight ratio, high stiffness-to-weight ratio, good durability and corrosion resisting capacity. However, its applications are limited so far due to several factors including lack of standards and design guidelines, lack of experience of designing structures with anisotropic and viscoelastic properties, and most importantly the lack of proper and reliable joining details.

Performance of an FRP structure depends on strength of its connections. This paper focuses on bearing-type bolted connections of FRP members. The strength is influenced by several factors such as connection geometry, fiber orientation, stacking sequence, friction and bolt torque, clearance of holes, cover plate stiffness, and so on. In bearing type multi-row bolted connections, load is not distributed equally among rows of bolts due to stiffness of cover plate[1), varying bolt position, and bolt-hole clearance. Several studies were performed, and some of the results were included in design standards and guidelines of FRP structures. For example, ASCE LRFD Pre-Standard[2) provides design formula for bolted connections with rows up to four rows where a steel cover plate or an FRP cover plate with half the stiffness of the FRP main plate is used. However, how cover plate stiffness affects the ultimate strength of the multi-row connection has not yet been studied.

This paper is aimed to investigate the effects of cover plate stiffness on ultimate strength of bearing type multi-row, double-lap FRP composite connections using 3D finite element analysis with a progressive damage model.

2. DAMAGE ANALYSIS

2.1 Failure criteria

The failure criteria of Chang and Lessard[3) has been modified and proposed the modified criteria in this study. The criteria consider two principal damages: a) fiber damage; b) matrix damage. Fiber failure criterion is further classified in compression and tension. Each of the damage modes is predicted by the following expressions:

Fiber failure in tension: $$\hat{\sigma}_{11} \geq 0 \quad F_{ft} = \left(\frac{\hat{\sigma}_{11}}{X_T}\right)^2 + \frac{\frac{\hat{\tau}_{12}^2}{2G_{12}^2}+\frac{3}{4}\alpha\hat{\tau}_{12}^4}{\frac{S_{12}^2}{2G_{12}^2}+\frac{3}{4}\alpha S_{12}^4} + \frac{\frac{\hat{\tau}_{13}^2}{2G_{13}^2}+\frac{3}{4}\alpha\hat{\tau}_{13}^4}{\frac{S_{13}^2}{2G_{13}^2}+\frac{3}{4}\alpha S_{13}^4} = 1 \tag{1}$$

Fiber failure in compression: $$\hat{\sigma}_{11} < 0 \quad F_{fc} = \left(\frac{\hat{\sigma}_{11}}{X_C}\right)^2 + \frac{\frac{\hat{\tau}_{12}^2}{2G_{12}^2}+\frac{3}{4}\alpha\hat{\tau}_{12}^4}{\frac{S_{12}^2}{2G_{12}^2}+\frac{3}{4}\alpha S_{12}^4} + \frac{\frac{\hat{\tau}_{13}^2}{2G_{13}^2}+\frac{3}{4}\alpha\hat{\tau}_{13}^4}{\frac{S_{13}^2}{2G_{13}^2}+\frac{3}{4}\alpha S_{13}^4} = 1 \tag{2}$$

Matrix failure: $$F_m = \left(\frac{\hat{\sigma}_{22}}{Y}\right)^2 - \frac{\hat{\sigma}_{33}\hat{\sigma}_{22}}{YZ} + \left(\frac{\hat{\sigma}_{33}}{Z}\right)^2 + \frac{\frac{\hat{\tau}_{12}^2}{2G_{12}^2}+\frac{3}{4}\alpha\hat{\tau}_{12}^4}{\frac{S_{12}^2}{2G_{12}^2}+\frac{3}{4}\alpha S_{12}^4} + \frac{\frac{\hat{\tau}_{13}^2}{2G_{13}^2}+\frac{3}{4}\alpha\hat{\tau}_{13}^4}{\frac{S_{13}^2}{2G_{13}^2}+\frac{3}{4}\alpha S_{13}^4} + \frac{\frac{\hat{\tau}_{23}^2}{2G_{23}^2}+\frac{3}{4}\alpha\hat{\tau}_{23}^4}{\frac{S_{23}^2}{2G_{23}^2}+\frac{3}{4}\alpha S_{23}^4} = 1 \tag{3}$$

where, $Y = \begin{cases} Y_T & \text{for } \hat{\sigma}_{22} \geq 0 \\ Y_C & \text{otherwise} \end{cases}$ and $Z = \begin{cases} Z_T & \text{for } \hat{\sigma}_{33} \geq 0 \\ Z_C & \text{otherwise} \end{cases}$

Above equations $\hat{\sigma}_{ij}$ are the components of the effective stresses, X_T, X_C Y_T, Z_T and Y_C, Z_C denote tensile and compressive strengths in the respective directions. S_{ij} are shear strengths with respective plane. α is a parameter representing the non-linear relationship of the shear strain and shear stress.

2.2 Constitutive law

FRP materials show elastic-brittle in nature; that is, damage in these materials is initiated without significant plastic deformation. Therefore, plasticity can be neglected when modeling the behavior of such materials. This study adapted the constitutive damage model proposed by Meer and Sluys[4). In their model, damage affects only diagonal terms of compliance matrix. The modulus of elasticity in the fiber direction E_{11} is degraded by the fiber damage variable d_f, and the moduli E_{22}, E_{33} in the direction transverse to the fiber direction and shear moduli G_{12}, G_{13} and G_{23} are degraded by the matrix damage variable d_m. The damage variables can be evaluated by the following equation.

$$d_i = \frac{\varepsilon_{i,eq}^F\left(\varepsilon_{i,eq}^{max} - \varepsilon_{i,eq}^0\right)}{\varepsilon_{i,eq}^{max}\left(\varepsilon_{i,eq}^F - \varepsilon_{i,eq}^0\right)}; \quad \varepsilon_{i,eq}^0 \leq \varepsilon_{i,eq}^{max} \leq \varepsilon_{i,eq}^F; \text{ and } \varepsilon_{i,eq}^{max} = \max\left(\varepsilon_{i,eq}^{max}, \varepsilon_{i,eq}\right) \tag{4}$$

Where i denotes the mode of failure, $\varepsilon_{i,eq}^0$ is the initial equivalent strain at which the failure criterion for the mode was met, and $\varepsilon_{i,eq}^F$ is the strain at which the material is completely damaged $(d_i = 1)$ in this failure mode. The $\varepsilon_{i,eq}^F$ is assumed to be $10^{10}\varepsilon_{eq}^0/L_c$ to keep the maximum equivalent stress equal to the initial equivalent stress $\sigma_{i,eq}^0$ up to 98% material damage. The equivalent strains can be calculated for the fiber failure as $\varepsilon_{f,eq} = \sqrt{{\varepsilon_{11}}^2 + \gamma_{12}^2 + \gamma_{13}^2}$ and for matrix failure as $\varepsilon_{m,eq} = \sqrt{\varepsilon_{22}{}^2 + \varepsilon_{33}{}^2 + \gamma_{12}^2 + \gamma_{13}^2 + \gamma_{23}^2}$. L_c is a characteristic length which is used to eliminate the mesh dependency. The equivalent stress-strain relation is valid only for the uniaxial deformation.

3. MATERIAL PROPERTIES AND MODEL DESCRIPTION

In this study, bearing type, two to four rows of bolted connections with a double-lap configuration are examined. The main plate is a FRP composite plate with a thickness of 12 mm. Steel bolts with diameter of 16 mm and a bolt hole diameter of 17.6 mm are used. A thicknesses of FRP cover plates is 6, 9, or 12 mm, that of steel cover plates is 3, 4.5, or 6 mm. These cover plate thicknesses correspond to stiffness ratios of cover plate to main plate of 1.0, 1.5, and 2.0 for FRP cover plates and 7.35, 11.03, and 14.70 for steel cover plates, respectively. Geometric parameters of bolted connections are set to satisfy code-specified minimum requirements, where a pitch to bolt diameter (p/d) ratio, a width to bolt diameter (w/d) ratio, and an end distance to bolt diameter (e/d) ratio are 4.0, 4.0, and 2.0, respectively.

For FRP plates, a laminate with a symmetric stacking sequence using quasi-isotropic glass-fiber is considered. Material properties of unidirectional lamina used in this study are given in Table 1. Shear moduli and shear stresses in all planes consider the same value. Material properties of steel are Young's modulus $E = 200$ GPa, Poisson's ratio $\nu = 0.3$.

Table 1 Material properties of unidirectional lamina

E_{11} (MPa)	$E_{22} = E_{33}$ (MPa)	$\nu_{12}=\nu_{12}=\nu_{12}$	G_{12} (MPa)	X_T (MPa)	X_C (MPa)	$Y_T=Z_T$ (MPa)	$Y_C=Z_T$ (MPa)	S_{12} (MPa)
32100	5740	0.33	1240	722	230	14	34	54.6

Finite element models are created using the general purpose finite element software, ABAQUS, with solid composite elements, C3D8R. Contact pairs are defined between faces of bolts and plates, and a main plate and a cover plate. Due to symmetry conditions, a quarter of a connection is modeled, and symmetry boundary conditions are applied in the planes.

4. RESULTS AND DISCUSSION

To verify the constitutive model and failure criteria, nonlinear progressive damage analyses are performed and predicted failure modes and ultimate strengths of the tested connections by Khashaba et al.[5] with good degree of accuracy, where the differences between the measured and the predicted ultimate strengths are about an order of 10%.

Strength ratios ($R_S = F/F_{BF6.0}$) of the connections analyzed in this study are shown Fig.1. where F= Strength of connection, and $F_{BF6.0}$= Strength of connection 'nBF6.0'.The connections with FRP cover plates take higher load compared with the connections of steel cover plate. For steel cover plate with a thickness half of the main plate thickness, ultimate strengths decrease by about 8.4%, 11.8% and 13.4% for two rows, three rows and four rows of bolted connections, respectively, when compared to ???. In Fig. 2 shows the strength ratio with the stiffness ratio ($R_E = 2K_c/K_m$) of cover plates, where K_c= cover plate stiffness, and K_m= main plate stiffness. It is observed that ultimate strength of the bearing-type bolted connection decreases with the increase of cover plate stiffness.

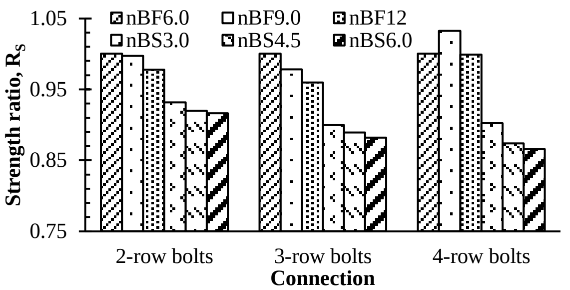

Fig.1 Effect of cover plate on ultimate strength

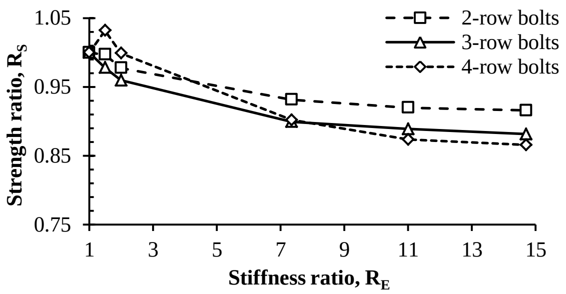

Fig.2 Effect of cover plate stiffness on ultimate strength

5. CONCLUSIONS

A set of failure criteria is proposed with the constitutive material law to predict failure modes and ultimate strength of the FRP composite structures. The proposed model is good agreement with the experimental results available in literature. For multi-row bearing-type bolted connections, strength of connection is affected by the cover plate stiffness. A connection with higher cover plate stiffness tends to show lower strength.

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