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Effect of Ply Thickness on The Bearing Capacity of Bolted-Fiber Cemboard: Numerical Modelling Using FEM

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Abstract: Fiber cemboard is one of the most important materials used in the construction of buildings. The application of fiber cemboard has led to the pre-fabricated and build-up system known as bolted-fiber cemboard to be used as floor system. Therefore, this study aims to numerically investigate the bearing capacity and slip-displacement of bolted-fiber cemboard. The numerical modelling involves two-ply fiber cemboard with size 210 mm length, 210 mm width and various thicknesses ranging from 9 mm to 20 mm. The bolted-fiber cemboard under push-out test was modeled in WELSIM. The results of stress-forces curves and stress-displacement curves were obtained. It was found that the higher the thickness of fiber cemboard, the higher the bearing capacity. The thicker fiber cemboard used does provide better performance of bearing capacity but it could lead to higher-slip displacement due to higher rate of damage. Overall, the final result of this study shows that bolted-fiber cemboard has a good potential as a structural member due to the excellent serviceability.

Keywords: Cemboard, Bolted-Fiber Cemboard, Bearing Capacity, Slip-Displacement, Push-Out Test

1. Introduction

Fiber cemboard has become a better alternative to plywood and chipboard. Beyond doubt, fiber cemboard with nominal density of 1390kg/m3 is a lightweight material that provide easy handling and installation. Moreover, fiber cemboard is recognized for its quality, reliability, and durability. Fiber cemboard is asbestos-free and produced from natural raw materials such as concrete calcareous, cellulose and water [1]. Fiber cemboard is specially designed for application in high humidity where environment impact resistances control such fire and water are required [2], [3]. In Malaysia, the typical applications of fiber cemboard are as wall, roof, floor and gable end panels. As for floor, fiber cemboard can be used as permanent formwork for concrete as similar as corrugated steel sheet. Attempts to

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improve the flexural and slip resistances have led to the use of steel bolts in multi-layer fiber cemboard. The presence of steel bolts that act as connector and bond mechanism has apparently improved the stiffness [4].

Heavy-duty floor system using multi-layer fiber cemboard is a new direction in the construction of buildings. Since the available thickness of fiber cemboard is insufficient for the heavyweight, it needs a greater number of ply where several layers can be bonded together using steel bolts. Currently, polyurethane adhesive is employed to bond the fiber cemboard. Kelly [5] proved that the presence of steel bolts as connector and bond mechanism able to increase the stiffness and durability. However, the use of steel bolts may contribute to the unexpected events such as high stress accumulation, delamination and cracking. Several factors such as size of steel bolt and thickness of ply are also governing the performance of multi-layer fiber cemboard. Currently, experimental study on flexural and slip resistances of fiber cemboard is not well developed. Although, Gamdomkar et al. [6] proposed the push-out test to determine the slip resistance, but large number of specimens must be prepared that consume a great deal of cost and repetitive works.

In order to overcome these problems, the finite element method can be adopted. Numerical modelling using the finite element method is a great tool to ensure this study can be conducted precisely and economically. Using the finite element method, a whole set of simple solutions of partial differential equations can be developed at various points of source for the approach to the internal entity displacement and stress fields [7]. This study focuses on the numerical modelling of bolted-fiber cemboard using finite element method. Therefore, a program known as WELSIM was used in the numerical modelling. The dimension of fiber cemboard is 210 mm width, 210 mm length and various thicknesses ranging from 12 mm to 20 mm. The steel bolt is used as connecter and acts as bond mechanism where it has 8 mm diameter. In-depth understand on the performance of bolted-fiber cemboard term of load bearing, slip-displacement and failure mode were obtained. The findings enable researchers and engineers to design the multi-layer fiber cemboard for heavy-duty floor system.

2. Fiber Cemboard

The first piece of fiber cemboard was made by using Hatschek process. Fiber cemboard is known as a substance of reinforced cement sheet product which contain 1% to 15% fiber (either natural or synthetic or combined), Portland cement slurry in weights from 40% to 80%, 2% to 15% clay and the thickener ranges between 0.03% and 0.5%. Fiber cemboard may contains silica by weight between 10% to 40% that act as filler in the composite mixture [8]. Since the composite mixture used in fiber cemboard is non-asbestos and green materials, thus environmental issues can be resolved, and future risks can be minimized by healthier and more effective alternate access. The use of fiber during the production of fiber cemboard provides better performance in term bending strength. However, Khorami [8] stated that a relative increase in bending strength could also increase other resistance properties such as fracture and ductility.

In general, fiber cemboard is produced with different thickness around 10 mm to 20 mm. Therefore, the application of fiber cemboard in building depend on its thickness. Ahmad et al. [9] mentioned that the compressive strength of fiber cemboard improved with thicker ply, but it affects the elastic modulus that tend to decrease. One of fiber cemboard most desirable qualities is its durability. Fiber cemboard is a non-burning and non-flammable fireproof material. It is also water-resistant and moisture resistant. This can be expressed as it still maintains performance stability and does not sink or deform in semi-open air and high humidity environments. Apart from that, it is easy to build with operation of the dry mode, economically beautiful with smooth surface, over long life, resist to corrosion, and does not damaged by moisture and insects. Due to its strength and durability, fiber cemboard is practically used in many countries for the construction of buildings. However, there are limited studies specifying the design consideration and specification of fiber cemboard [10].

In Malaysia, fiber cemboard has been used as floor system in many commercial buildings. However, the used of fiber cemboard for heavyweight slab which normally require 125 to 200 mm thickness is strictly prohibited due to the limited studies on the load bearing capacity. Previous studies by Dohring [11] use fiber cemboard as floor panel for outdoors. He found out that cement fiber panels are one of the typically appropriate which can be quickly handled, and coupling methods are particularly important. A study on the physical, mechanical and thermal properties of lightweight cemboard coconut fiber have been calculated after 28 days of hydration were made by Asasutjarit et al. [12]. Fiber-length, coir's pre-treatment and mixture ratio were the parameter tested. The thermal properties of the specimens studying coconut coirs have revealed that light weight cement boards have lower thermal conductivity relative to the industrial composite board and reached the best accepted mechanical requirements.

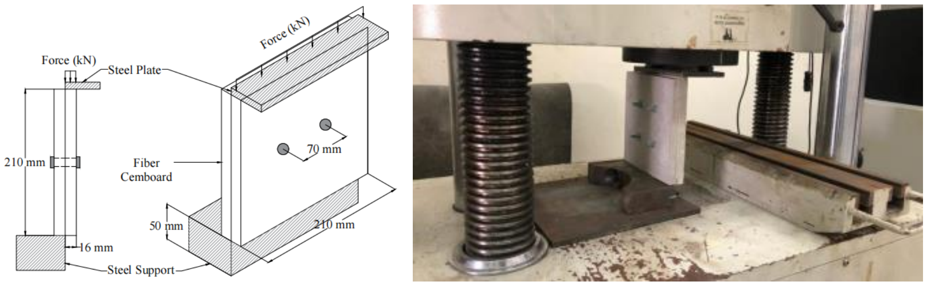
3. Bearing Resistance and Slip-Displacement

Bearing capacity is the ability of a structure to safely carry in-plane pressure without shear failure. It is basically referred as resistance parameters in term of bearing resistance, slip-displacement and toughness. In major cases, bearing capacity governed by allowable bearing capacity, ultimate bearing capacity and safety factor. The ultimate bearing capacity is the theoretical limit of the bearing capacity. The fiber can also be known to increase the load-bearing capability of cement boards. As a structure that used for floor system, thickness is the most factor that influence the bearing capacity. Garber [13] emphasized that the bearing capacity can be enhanced by increasing the thickness.Tian et al. [14] suggested that a floor system should has bearing capacity roughly 15 kN/m^2 at mid-span distortion, while the final load around 22.5 kN/m^2. Bearing capacity is usually determined through experimental study [15]. There are three common methods to identify the bearing capacity; pull-out test, push-out test and tensile test.

A method to find out the bond strength between two different elements is named as pull-out test. This experimental study is basically conducted for fiber or disc that embedded in concrete. The basic principle behind this experimental study is to produce a result of pull-out force, which corresponds closely to the compressive strength of concrete. The force that requires to pull a fiber or disc out from hardened concrete into which it has been cast is considered as pull-out forces. Push-out test is conducted for composite material to measure the bonding energy on the interface and the frictional sliding effects. Bouchair et al. [16] stated that the time-consuming and expensive conventional testing methods have led to the utilization of push-out test. In addition, it is a safe and accurate way to assess the critical characteristics. Owing to its efficiency, push-out test is the most effective form of assessment [17]. Push-out test can be conducted by adding a dispersed load to the top of specimen.

4. Numerical Modelling using FEM

Numeric modelling is a mathematical representation of the behavior in physics (or other) based upon appropriate hypotheses and assumptions [18]. Since the numerical modelling is conducted based on the push-out test, hence the experimental study becomes essential as a platform of appraisal and validation. In this study, the experimental study conducted by Norhalim and Jaini [19] was used for the numerical modelling. The experimental study was used bolted-fiber cemboard with dimension of 210 mm width, 210 mm length and 16 mm thickness. The push-out test was performed using the Universal Testing Machine with maximum capacity of 1000 kN. During the experimental study, steel plate was placed at the bottom and top sides of bolted-fiber cemboard as can be seen in Figure 1. The steel plate at the bottom side acts as the support, while the steel plate at the top side was imposed with the loading. The stroke as controlled incremental displacement with speed rate of 1.0 mm/minute was utilized to yield the force-displacement curve.

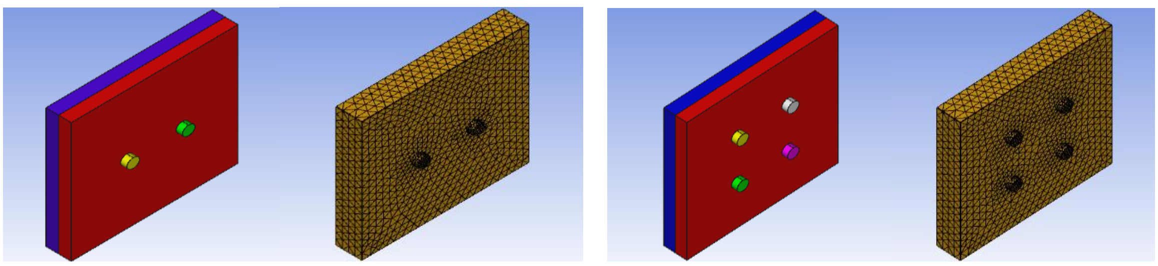


a) b)

Figure 1: Push-out test – a) Schematic testing, and b) Actual testing

The Finite Element Method (FEM) is a numerical analysis technique used to obtain approximate solutions to a wide range of engineering problems appeared in 1960 [20]. FEM is the one previously developed by the authors with a crack queuing algorithm integrated for discrete crack analysis [21], [22]. Through testing specimens examined by others and testing against the reported test findings, its applicability and accuracy have been checked [23]. The application of FEM is widely used in many fields. FEM was used to model all sorts of structures (steel, concrete, wood and masonry) and to simulate the relationship between soil and structure [24]. In this study, the numerical modelling was performed using the finite element method program so-called WELSIM. This software has been used in structural engineering to solve various problems related to the solid mechanics, heat transfer and fluid interaction. Moreover, WELSIM provides ascendancy in the numerical modelling of continuum and fracture failure that allow the sightings of real behavior.

Specifically, the numerical modelling provides description and comparison of the results of experimental study. The bolted-fiber cemboard was modelled in the three-dimensional. Therefore, the four-noded element so called solid tetrahedral was utilized to discretize the fiber cemboard and steel bolts. Figure 2 shows the geometry of bolted-fiber cemboard with the designation mesh. In this study, mesh size of 10 mm was found highly compatible to generate accurate results and progress with time-efficient data. In general, the mesh size can be determined from the convergency and critical time measurements. Fiber cemboard can be considered as heterogenous material due to the presence of two different components, while steel bolt is fully isotropic-homogenous material. In order to satisfy the nonlinear and plastic behavior, the elastic material properties, strength parameters and hardening properties were defined on the fiber cemboard and steel bolt as tabulated Table 1 and Table 2.



a) b)

Figure 2: Geometry and discretization of bolted-fiber cemboard – a) Model FC2B, and b) Model FC4B

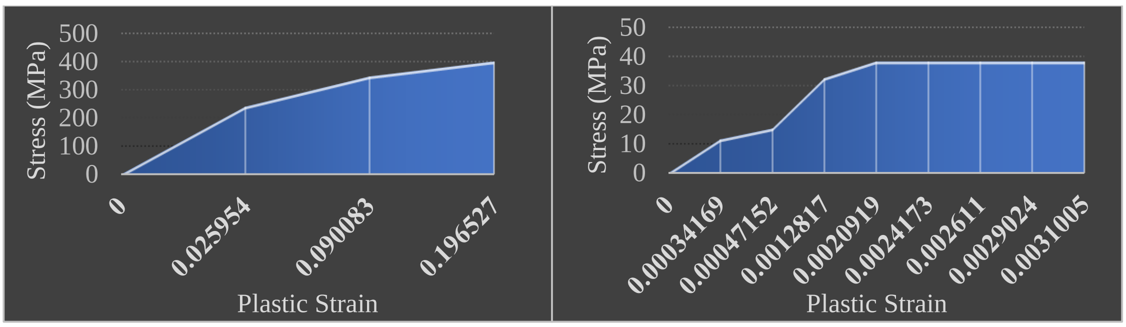
Table 1: Material properties of fiber cemboard [8]

Properties	Value
Young's modulus, *E* (GPa)	33
Poisson Ratio, *v*	0.20
Density, ρ (kg/m^3)	1300
Bulk Modulus, k (GPa)	15.625
Shear Modulus, G (GPa)	12.712
Tensile Strength, σ_t (MPa)	6.37
Isotropic Thermal Conductivity, (W/m/K)	0.24
Specific Heat, (J/kg/C)	780

Table 2: Material properties of steel bolt [25]

Properties	Value
Young's modulus, *E* (GPa)	210
Poisson Ratio, *v*	0.303
Density, ρ (kg/m^3)	7850
Bulk Modulus, k (GPa)	166.7
Shear Modulus, G (GPa)	76.92

Plasticity occurs after the material has been yielded. In a one-dimensional case, yielding occurs at a single stress value known as yield stress. There are four options that describe the various forms of actions of the substance in WELSIM software which are bilinear kinematics hardening, multilinear kinematics hardening, bilinear isotropic hardening (BISO), and multilinear isotropic hardening (MISO). Multilinear kinematic hardening was associated to with material model of fiber cemboard while trilinear isotropic hardening was defined on steel bolt. On the other hand, the hardening properties require the definition of plastic strain and trues stress that derived theoretical from engineering strain and engineering stress. Figure 3, (a) shows multilinear kinematic hardening for fiber cemboard, whilst Figure 3, (b) shows trilinear isotropic hardening for steel bolt. Stress-strain curve is a graphical representation of material behavior under load. However, in numerical modelling it must be presented in the form of a plastic strain-stress curve.



a) b)

Figure 3: Plasticity – a) multilinear kinematic hardening for fiber cemboard, and b) trilinear isotropic hardening for steel bolt

5. Results and Discussion

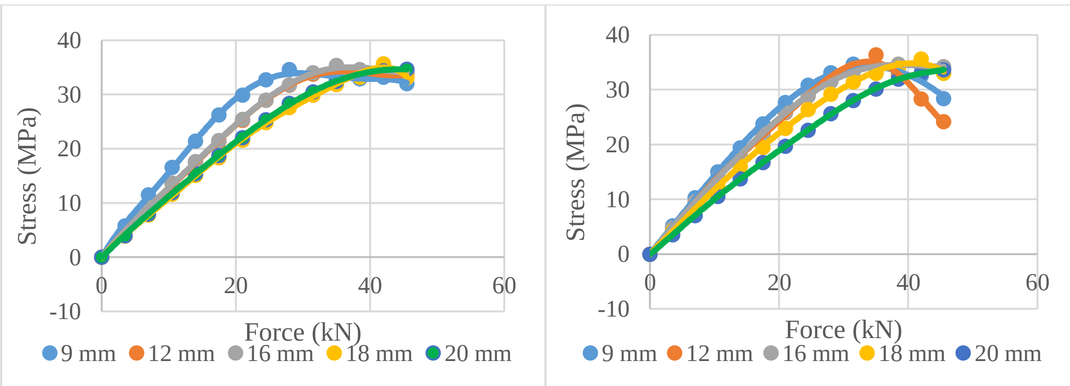
5.1 Stress-Force and Stress-Displacement

Results between numerical modelling and experimental study are compared as tabulated in Table 3. The results in term of bearing capacity and slip-displacement are for bolted-fiber cemboard with thickness 16 mm. It should be noted here that the experimental study is based on Norhalim & Jaini [19]. Model FC2B was found to be capable of resisting an axial compression load of 35.00 kN, which is 1.26% lower than the experimental analysis. Similarly, model FC4B has lower bearing capacity in numerical modelling as compared to experimental study. In numerical modelling, model FC4B able to sustain axial compression load up to 37.00 kN, whilst in experimental study it has 39.73 kN. This creates approximately 4.84% errors. On the other hand, the slip-displacement of model FC2B has 33.44% difference between numerical modelling and experimental study. The slip-displacement for model FC4B is 3.03 mm and 4.36 mm for numerical modelling and experimental study, respectively.

Table 3: Results between numerical modelling and experimental study

Model	**Parameter**	**Experimental Study**	**Numerical Modelling**	**Error (%)**
FC2B	Bearing Capacity (kN)	35.44	35.00	1.26
	Slip-displacement (mm)	4.31	3.23	33.44
FC4B	Bearing Capacity (kN)	39.73	37.00	4.84
	Slip-displacement (mm)	4.36	3.03	43.56

Prior to the successful of numerical modelling, models FC2B and FC4B were simulated under parametric studies. The results of stress-force curves for different thicknesses of fiber cemboard; 9 mm, 12 mm, 16 mm, 18 mm and 20 mm are plotted as can be seen in Figure 4. The force obtained from numerical modelling is considered as bearing capacity. It can be observed that the pattern of stress-force curve is similar for all parametric studies and imply both models. Stress increases as the force correlates and stays stable until the yield stress is reached. In a push-out test, the fiber cemboard able to resist the stresses generated by axial compression load up to failure. While all parametric studies for both models FC2B and FC4B demonstrate similar yield stress, the stiffnesses shown by the gradient of the stress-force curves and the final loads at the initial point of the yield stress are diverse.



a) b)

Figure 4: Stress-force curves – a) model FC2B, and b) model FC4B

There are five different curves that represent the parametric studies fiber cemboard thickness in 9 mm, 12 mm, 16 mm, 18 mm and 20 mm. The displacement is determined at the initial point of the yield stress as it assumed to be slip-displacement due to the axial compression load. Under the axial compression load, the bolted-fiber cemboard moves downward to a certain limit. Initially, the movement is resisted by polyurethane glue which serves as a bond mechanism. When the detachment happened, the resistance toward movement is shifted to steel bolt. Stress grows when it correlates to the displacement and is constant until the yield stress is reached. The displacement subtraction between parametric studies also shows a more noticeable basis. The stress-displacement curve for model FC2B shows results as expected where as the thickness increase, the slip-displacement decrease however, it is different for model FC4B as shown in Figure 5.

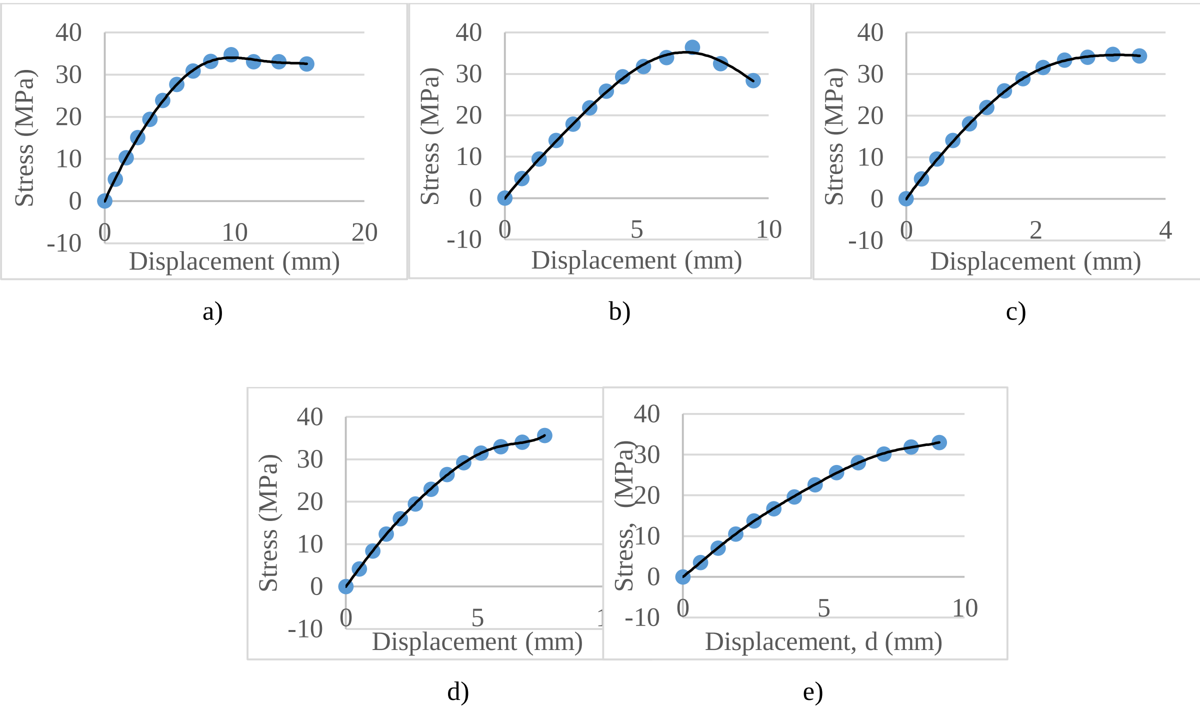
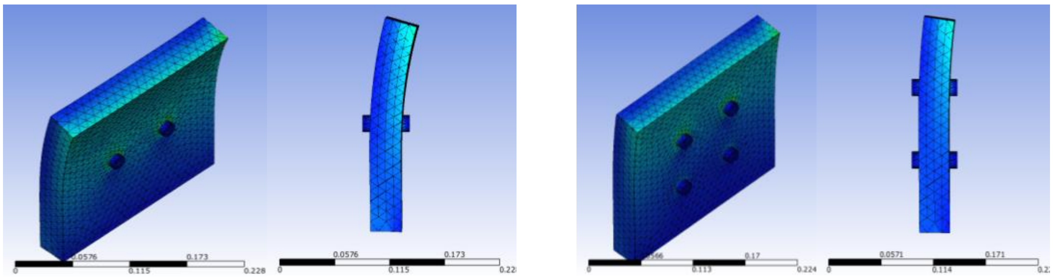


Figure 5: Stress-Displacement curves for model FC4B with fiber cemboard thickness – a) 9 mm, b) 12 mm, c) 16 mm, d) 18 mm, and e) 20 mm

5.2 Failure Mode

Ummi et al. [26] claimed that plate with a bolt connection will fail in tension. The plate is deformed as the in-plane load is applied and increased, while the edge folds over and the bolt hole is deformed. Such behaviour was observed on bolted-fiber cemboard. Figure 6, (a) illustrates the damage to deformation occurs on model FC2B. Meanwhile, the damage to deformation on model FC4B can be seen in Figure 6, (b). It can be observed that regardless of the fiber cemboard thickness, the damage happens in the surrounding steel bolt. This type of damage is known as flaking. If sudden force is applied on the bolted-fiber cemboard, the flaking become severe and may cause spalling and facture. Another damage that can be seen is the bending where the fiber cemboard deforms such as the semi-buckling shape. Although the slip-displacement is confirmed, it cannot be visualized herein can only be quantified.

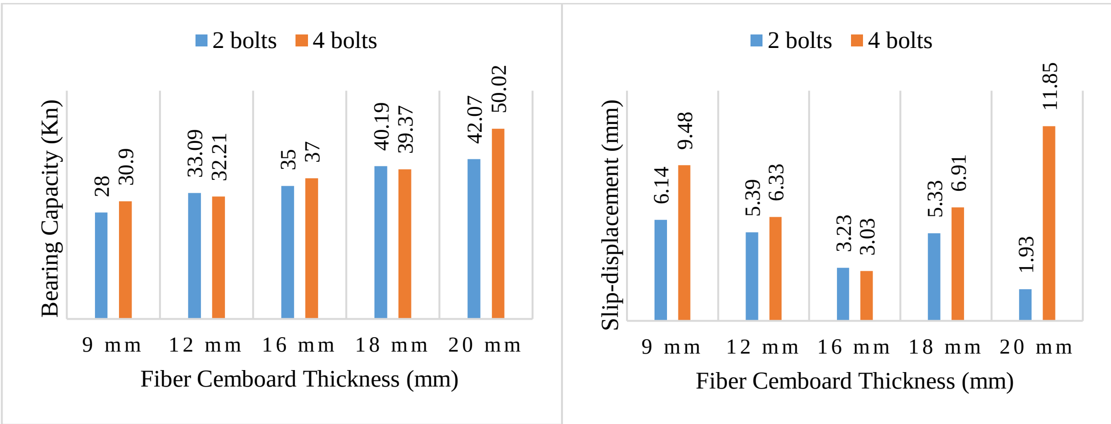


a) b)

Figure 6: Damage to deformation on model - a) FC2B, and b) FC4B

5.3 Effect of Fiber Cemboard Thickness

Figure 7, (a) shows the bearing capacity of models FC2B and FC4B in correspond to the thickness of fiber cemboard. When thicker fiber cemboard is used, the bearing capacity increased steadily. Joohari and Amin [27] stated that the increasing in thickness was found to improve the strength of flat slab and minimize the deflection. For model FC2B, the increment of bearing capacity is around 10% to 35%. On the other hand, model FC4B has 10% to 40% increment of bearing capacity in correspond to the thickness of fiber cemboard. The effect of thickness on the slip-displacement of bolted-fiber cemboard is depicted in Figure 7, (b). It can be observed that as the fiber cemboard thickness is increased, the slip-displacement decreases gradually. However, the trend of decrement only true for thickness of 9 mm to 16 mm only. Model FC4B with thickness of 20 mm shows higher slip-displacement due to the higher rate of damage. Although the use of thicker fiber cemboard contributes to better performance of bearing capacity, unlikely the slip-displacement shows opposite behavior.



a) b)

Figure 7: Different fiber cemboard thickness effects on – a) bearing capacity, and b) slip-displacement

6. Conclusion

In this study, it was justified that the thickness of fiber cemboard has significant relationship with the bearing capacity and slip displacement of bolted-fiber cemboard. Analysis of numerical modelling revealed that the bolted-fiber cemboard have higher amount of bearing capacity as the thickness is increasing. The thicker fiber cemboard used does provide better performance of bearing capacity but it could lead to higher-slip displacement due to higher rate of damage. The connection failure and deformation of bolted fiber cemboard were analysed directly based on the stress distribution and the deformation. The contact between bolt and fiber cemboard produced high concentration of stress around the steel bolts. The deformation of bolted-fiber cemboard also can be seen as the load was applied, the fiber cemboard deforms to semi-buckling shape. It can be concluded that the thickness of bolted-fiber cemboard possess significant effect on the slip-displacement and working load.

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