ANALYTICAL STUDY OF FLEXURAL BEHAVIOR OF VARIOUS COMPONENTS UTILIZING THE FORMWORK PANELS MADE OF HIGH-STRENGTH CONCRETE

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Abstract - Using a new generation formwork system made from high-strength concrete is an advanced construction approach, not only reducing construction time but also improving the surface quality and enhancing the load-bearing capacity of reinforced concrete (RC) structures. This study aims to investigate the flexural behavior of RC components when using the novel formwork system was investigated to clarify its effectiveness in enhancing the flexural performance. For this purpose, a series of simulations with different scenarios corresponding to flexural components, including columns, beams, walls, and floors, were conducted. The results show that high-strength concrete formwork combined with stainless steel or FRP-reinforced materials helps increase the flexural capacity of the resulting components. Ensuring the bond between the formwork layer and the in-situ concrete is essential to maintain the loading-bearing behavior for thin components such as floors and walls because it significantly affects the effective cross-section of the element.

Key words - Concrete formwork; Finite Element Method; Flexural behavior; High-strength concrete; FRP grids

1. Introduction

The continuous improvement of construction methods combined with advanced material solutions is a key factor in the development of the construction industry. Recently, the construction method of using permanent precast concrete formwork to replace traditional wooden, plastic, or steel formwork has attracted the attention of many construction corporations and scientists [1, 2]. With this approach, the removal of the formwork after construction is eliminated, thereby shortening construction time and reducing labor safety risks. This method is particularly suitable for projects with difficult construction conditions, such as underground works, as well as components built at height or underwater. Additionally, using formwork can enhance the surface quality of components, as the formwork can be manufactured at a precast component factory with a controlled production process. Furthermore, if the formwork is made from high-strength concrete reinforced with non-corrosive steel or non-metal materials [3], the formwork itself becomes part of the effective load-bearing section of the structure, helping to improve structural performance by limiting crack formation, delaying the yield point of the reinforcement within the component, and thus increasing the structure's resistance.

Given these many advantages, concrete formwork has recently been applied to several construction projects [4, 5]. However, most of these projects use precast concrete formwork solely to reduce the need for formwork removal during construction, with little attention given to the impact of the formwork system on the load-bearing properties of the component itself. Meanwhile, numerous studies have conducted experiments to clarify the effectiveness of formwork in enhancing the structural performance of components. For example, Yin et al. [3] conducted experiments on beams using U-shaped formwork made of textile-reinforced concrete (TRC). Zhang et al. [6] used ultra-high-performance concrete (UHPC) formwork for the concrete casting of composite steel bridge deck slabs. Kojima et al. [7] and Fujikura et al. [8] used fiber-reinforced concrete formwork combined with stainless steel for column components. These studies all show that the use of formwork improves the flexural and shear strength of the component by increasing its stiffness and delaying the appearance of flexural and shear cracks on the component.

However, most of the aforementioned studies primarily focus on the behavior of components when using formwork for beams or columns. Meanwhile, precast concrete formwork systems can be applied to various types of components such as floors, beams, columns, walls, foundations, etc. Depending on the application, the permanent formwork can be used on one, two, three, or four sides of the component. In each case, the effectiveness of the formwork can vary significantly. Additionally, the bond between the formwork layer and the cast-in-place concrete layer, as well as the type of reinforcement material used in the formwork, are considered extremely important factors. With the limited number of experimental samples, the impact of changing these parameters has not been thoroughly investigated in previous studies.

Therefore, this study aims to clarify (i) the flexural behavior of different types of components, including columns, beams, walls, and floors, when using the new generation of permanent formwork systems; (ii) the influence of the bond between the formwork and the cast-in-place concrete layer; and (iii) the type of reinforcement mesh on the flexural behavior of components when using formwork. To achieve this goal, the study conducts a series of numerical analysis with differentformwork applications. The behaviors include the load-deflection relationship, the behavior of the load-bearing steel stresses, and the concrete stresses, all of which are analyzed in detail in the study.

2. Finite element modeling

2.1. Analysis cases

This study focuses on examining the flexural behavior of four types of components, including columns, beams, walls, and floors, in combination with 4, 3, 2, or 1 sides of formwork, as shown in Figure 1. Reinforcement bars D13 are used for the column and beam components, while D8 steel is used for the wall and floor components. The width of all four types of components is 300 mm, while the thickness is 300 mm for the columns and beams and 100 mm for the walls and floors. D8 hoops for beams and columns and D8 reinforcement (perpendicular orientation) for walls and floors are arranged as shown in Figure 1.

For each case, the reinforcement material inside the formwork and the bonding characteristics between the formwork and the cast-in-place concrete are the two basic parameters that are varied in the simulations, as shown in Table 1. In all cases, the formwork has a thickness of 20 mm. There are two reinforcement mesh configurations within the formwork: stainless steel bars D4 with a spacing of 100 mm or FRP non-metallic mesh with bars D2 and a mesh spacing of 75 mm. Additionally, the bond between the formwork and the component is considered an important variable. To clarify this effect, the study changes the bonding conditions for two cases, including a rigid bond and a case accounting for potential debonding between the formwork and the cast-in-place concrete, detailed in section 2.2. Furthermore, control samples for columns, beams, or walls and floors without formwork are also simulated, as shown in Table 1.

The two-point bending load scheme is applied in the analysis model for the column and beam components, as well as the wall and floor components, respectively, as illustrated in the upper and lower parts of Figure 2. The boundary condition of a simply supported beam is established at the support positions.

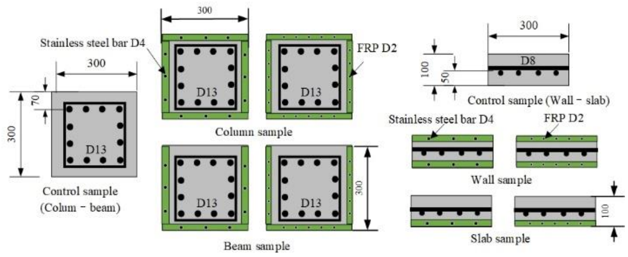


Figure 1. *Cross-section of analysis cases*

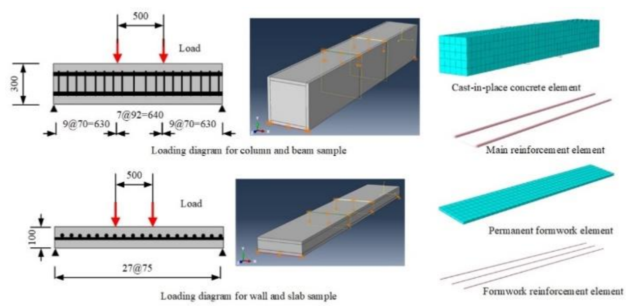


Figure 2. *Loading diagram and elements of analysis model*

Table 1. *Analysis cases and their parameters*

Component type	Name	Cast-in-place concrete	Formwork concrete	Main reinforcement	Reinforcement in formwork	Contact of formwork – cast-in-place concrete
Control samples (non-formwork)	DN (Column - beam)	M30	-	D13	-	-
	SN (Wall - slab)	M30	-	D8	-	-
Column (4 sides of formwork)	C-1	M30	M60	D13	Three of D4 bars	Rigid
	C-2	M30	M60	D13		Debonding
	C-3	M30	M60	D13	Five of D2 FRP bars	Rigid
Beam (3 sides of formwork)	D-1	M30	M60	D13	Three of D4 bars	Rigid
	D-2	M30	M60	D13		Debonding
	D-3	M30	M60	D13	Five of D2 FRP bars	Rigid
Wall (2 sides of formwork)	T-1	M30	M60	D8	Three of D4 bars	Rigid
	T-2	M30	M60	D8		Debonding
	T2-3	M30	M60	D8	Five of D2 FRP bars	Rigid
Slab (1 side of formwork)	S-1	M30	M60	D8	Three of D4 bars	Rigid
	S-2	M30	M60	D8		Debonding
	S-3	M30	M60	D8	Five of D2 FRP bars	Rigid

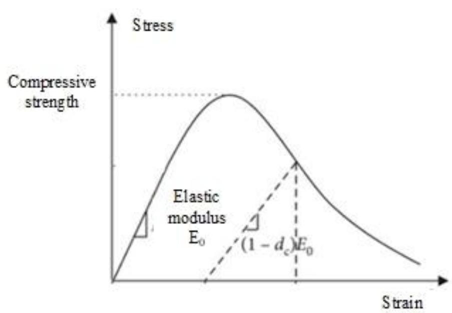
2.2. Material and bonding model

In the analysis model shown in Figure 2, three-dimensional solid elements are assigned to the concrete, and truss elements are assigned to the reinforcement of the beam and the reinforcement material inside the formwork. The basic material properties, including compressive strength, tensile strength, and elastic modulus, are shown in Table 2.

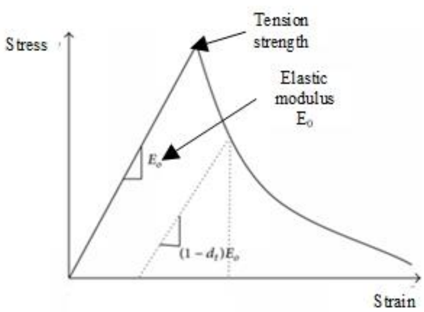
Table 2. *Material parameters used in analysis model*

Material type	Elastic modulus (GPa)	Strength MPa)	
		Compression	Tension
M30 concrete	30	30	4
M60 concrete	40	60	6
Steel	210	300	
FRP	70	-	

In all cases, the concrete compression zone is modeled using the nonlinear CDP model with a softening region, as shown in Figure 3(a), while the tensile zone is modeled using a nonlinear model as shown in Figure 3(b). These models are configured based on Abaqus support tools: the CDP Generator [9, 10]. The cast-in-place concrete of the component is ordinary concrete with a compressive strength of 30 MPa and a tensile strength of 4 MPa. Currently, high-strength or ultra-high-strength concrete is being widely developed. In this study, to balance mechanical strength, workability during formwork construction, and material cost, the concrete used for the precast formwork is high-strength concrete, with a compressive strength of 60 MPa and a tensile strength of 6 MPa.



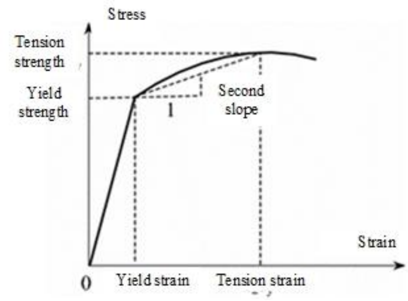
(a) Compression model of concrete



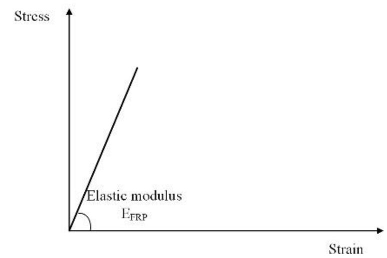
(b) Tension model of concrete

Figure 3. *Material model of concrete*

The values for the elastic modulus and strength of the steel in the component, as well as the reinforcement material in the formwork, are set as shown in Table 2. The structural reinforcement steel and the stainless steel in the formwork both use a nonlinear model, as depicted in Figure 4(a), based on the Abaqus support tool: Steel Material Generator [9, 11]. In cases where the formwork uses FRP non-metallic grid, the FRP material model uses a linear model, as shown in Figure 4(b), with an elastic modulus of 70 GPa, corresponding to the parameters of the GFRP grid. Since the beam sample reaches failure before the FRP grid reaches its tensile strength, the nonlinear model of the FRP grid is not considered.



(a) Steel model



(b) FRP model

Figure 4. *Material model*

On the other hand, the bond between the reinforcement steel and the cast-in-place concrete, as well as the bond between the reinforcement grid and the formwork concrete, is assumed to be rigid, in line with conventional theories of reinforced concrete components [12]. Meanwhile, the bond between the formwork and the cast-in-place concrete is an important variable that needs to be considered. If the bond between the two layers significantly affects the load-bearing capacity of the component, structural approaches such as roughening the formwork surface or adding shear keys should be implemented to enhance the bond between the formwork and the cast-in-place concrete. Therefore, in this study, two bonding conditions are considered: a rigid bond and a bond that accounts for potential debonding between the formwork and the cast-in-place concrete. In the debonding case, a cohesive model has been used to represent the bond between the formwork and the concrete [13]. In this model, parameters for the bond strength in the tensile and shear directions need to be defined. This means that the two materials will lose their bond when the stress on the contact surface exceeds these bond strength limits. In this study, the bond strength limit is set to 0.5 MPa for both directions, based on reference values from previous studies [14], assuming the formwork surface is not roughened prior to casting the component's concrete.

3. Results and discussions

3.1. Model validation

Before presenting the analysis results of components using the formwork system, the analysis results of the control beam and slab samples were compared with theoretical values based on reinforced concrete beam theory to validate the model [15]. The validation results for the control beam sample (DN) are shown in Figure 5. The calculated results, based on reinforced concrete beam theory for the DN sample, include the load at which flexural cracks appear at 42 kN, the load when the beam's reinforcement begins to yield at 140 kN, and the load when the concrete at the top of the beam begins to reach its compressive strength at 181 kN, indicated by dashed lines in Figure 5. Correspondingly, the analysis results for the stress distribution at these load points are also shown in Figure 5. It can be confirmed that the concrete begins to reach its tensile strength at the bottom of the beam at a load of 44 kN, the reinforcement starts to yield at a load of 152 kN, and the concrete begins to fail in compression at a load of 183 kN. Additionally, it is evident that the stiffness of the load-deflection relationship decreases significantly when cracks first appear in the concrete and when the reinforcement begins to yield. These results indicate that the analysis model aligns well with the calculated results based on reinforced concrete beam theory. Similar validation results were also confirmed to match the calculated results for the control slab sample (SN). Typically, model validation for components using formwork should be conducted based on experiments. However, comparison with theoretical beam calculations also shows reasonable results. Therefore, the established conditions, especially the material models, are considered to have a certain degree of reliability.

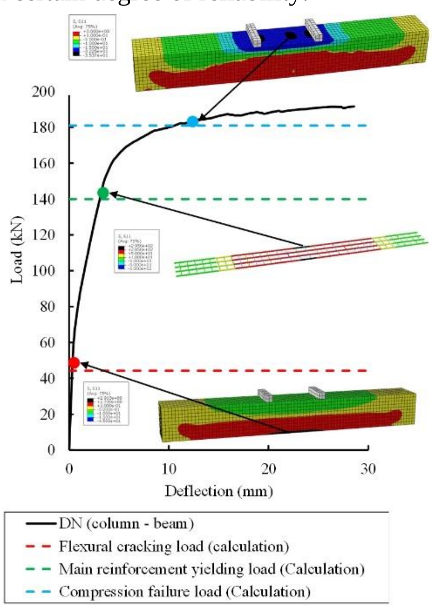
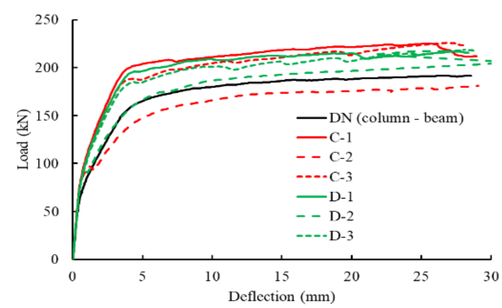


Figure 5. *Validation results of DN sample*

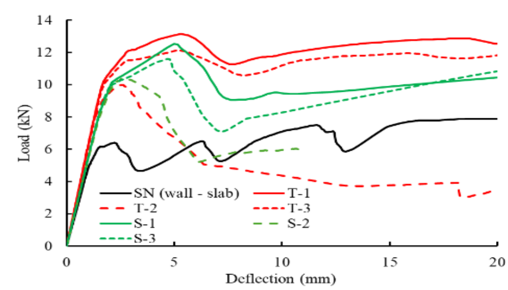
3.2. Load-deflection relationship and maximum load

The load-deflection relationship of the cases in Table 1 obtained from the simulations is shown in Figure 6. The symbols and colors of the lines in Figure 6 correspond to the cases in Table 1. Figure 6(a) shows that the behavior of cases using 4-sided formwork and 3-sided formwork is quite similar and resembles the behavior of the reinforced concrete beam without formwork (DN sample). Except for sample C-2, the remaining samples have a higher peak load than the DN sample without formwork by 5-20%. Additionally, samples using a rigid bond between the formwork and cast-in-place concrete exhibit higher peak loads than those using the model considering the debonding between the formwork and cast-in-place concrete (C-2 and D-2). This is because, after the debonding, the composite effect between the formwork and cast-in-place concrete is lost, reducing the formwork's effectiveness in the component. Moreover, the samples using stainless steel as reinforcement material have a slightly higher peak load than those using FRP grid. This is because steel, with its higher modulus of elasticity, can exert its effect earlier compared to FRP, which hasn't yet reached its yield point.

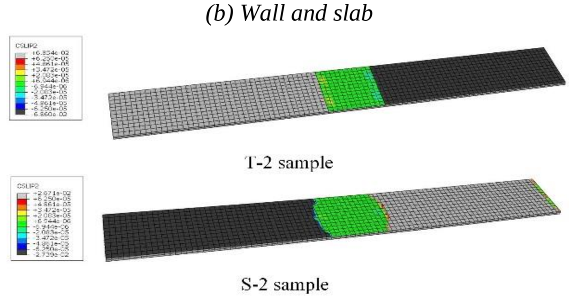
Similarly, Figure 6(b) also shows the enhanced flexural resistance of wall and slab components, with this effect being more pronounced compared to the case of columns and beams. The use of a softening model for the concrete's compression zone causes the load-deflection relationship to become unstable after the concrete starts to fail in all cases. Depending on the formwork conditions used, the enhancement of flexural resistance varies, but in general, the peak load in all cases is 1.7 to 2.2 times higher compared to the SN sample. FEM analysis results show that the enhanced flexural resistance in the case of using formwork for slabs or walls is greater than for beams and columns. This is because slab and wall components are thinner than beams and columns. In other words, for the same formwork size, the greater the proportion of formwork relative to the cast-in-place concrete, the higher the enhancement effect on the component's flexural resistance, and vice versa.



(a) Column and beam



(b) Wall and slab



(c) Debonding of T-2 and S-2 samples

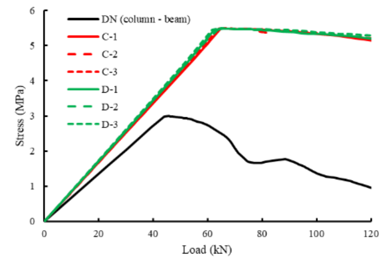
Figure 6. *Load–deflection relationship*

On the other hand, Figure 6(b) also shows that samples with a rigid bond between the formwork and cast-in-place concrete have a significantly higher peak load than those considering the debonding, while the samples using stainless steel show better performance than those using FRP as the formwork reinforcement material. Particularly, samples T-2 and S-2 experience a significant drop in load at the debonding point between the formwork and cast-in-place concrete. This phenomenon is illustrated in Figure 6(c), where the regions with sliding between the formwork and cast-in-place concrete are shown in black and gray. After the debonding, the load of samples T-2 and S-2 drops below that of the component without formwork. This is because the formwork takes up significant space, greatly reducing the cast-in-place concrete section of the wall and slab. Therefore, if the bond between the formwork and cast-in-place concrete is not ensured, the reduced section of cast-in-place concrete may lead to brittle failure, as shown in Figure 6(b). Meanwhile, when the bond is maintained, samples T-1 and S-1 still show higher loads than the SN sample after reaching the peak load. This highlights the importance of ensuring the bond between the formwork and cast-in-place concrete to prevent brittle failure of the component, especially for small-section components like walls and slabs.

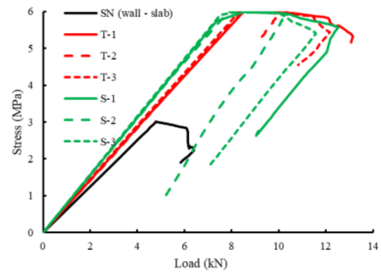
3.3. Effective in slowing down the appearance of cracks in concrete

An important advantage of using the new generation formwork is that it creates an external layer for the component and helps delay the appearance of cracks in reinforced concrete structures. This is because the formwork is made from high-strength concrete, which has a higher tensile strength compared to the concrete in samples without formwork. When the bond between the formwork and the cast-in-place concrete is ensured (before failure), the formwork system and the component can work simultaneously, similar to the composite beam effect, increasing stiffness and delaying the appearance of flexural cracks. This can reduce the risk of steel reinforcement corrosion in structures when formwork is used in components.

To clarify this phenomenon, Figures 7(a) and 7(b) show the relationship between load and tensile stress of the bottom concrete at the mid-span of the loaded span. It can be seen that the stress of the cast-in-place concrete (DN and SN samples) and the formwork concrete (in the other samples) begins to decrease after reaching its tensile strength, corresponding to values of 3 MPa and 6 MPa, respectively, indicating that the concrete starts to crack due to tensile stress. Thus, Figure 7 shows that using formwork can increase the cracking load by approximately 1.5 times compared to non-formwork samples, whether for columns, beams, walls, or slabs. The results in Figure 7 also show that the difference in cracking load is insignificant in cases where the bond between the formwork and the cast-in-place concrete varies. This is because, at this load stage, the stress on the interface between the two layers has not yet exceeded the bond limit of 0.13 MPa, so the bond has not yet failed.



(a) Column and beam



(b) Wall and slab

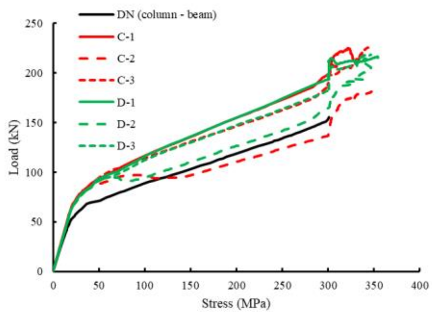
Figure 7. *Comparison of flexural crack loads between cases*

Additionally, the differences when changing the reinforcement material inside the formwork are minimal because, at the initial stage, the concrete still has tensile capacity, so the contribution of the reinforcement is not yet significant. Based on the results in Figure 7, it can be concluded that using formwork can delay the onset of cracks in the component, thus increasing the design load in the serviceability limit state and reducing the risk of steel reinforcement corrosion in real-world structures.

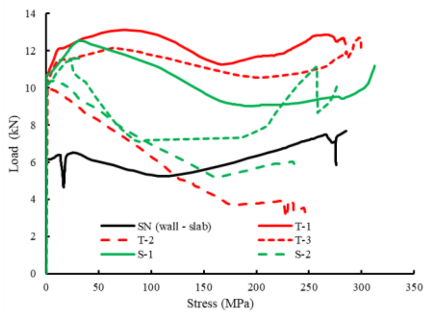
3.4. Tension stress of the reinforcement in the formwork

Figure 8 shows the relationship between load and tensile stress of the main reinforcement at the mid-span, with Figure 8(a) illustrating the case of column and beam components, and Figure 8(b) representing the case of wall and slab components. In Figure 8(a), it is observed that when the load exceeds the threshold of 44 kN, meaning after the appearance of cracks, the tensile stress of the reinforcing steel in the case with formwork is lower than that of the reference sample DN at the same load. However, for the C-2 and D-2 samples, at a load level of 100 kN, the tensile stress of the reinforcement suddenly increases and becomes equivalent to that of the DN sample. This is due to the debonding between the formwork and the cast-in-place concrete, which reduces the formwork's contribution to resisting the tensile stress acting on the beam, leading to a sudden increase in the tensile stress of the main reinforcement.

Additionally, after the reinforcement reaches the yield strength of 300 MPa, the stress values begin to lose stability in all cases due to the formation of cracks around the reinforcement. Thus, the results in Figure 8(a) indicate that when the bond between the formwork and the cast-in-place concrete is ensured, the formwork can delay the process of reaching the yield strength of the reinforcement. This can be explained by two reasons: (i) the occurrence of cracks in the component using formwork happens later compared to the component without formwork, and (ii) the tensile resistance of the component includes contributions from the stainless steel or FRP bars inside the formwork, in addition to the contributions from the main reinforcement of the component.



(a) Column and beam



(b) Wall and slab

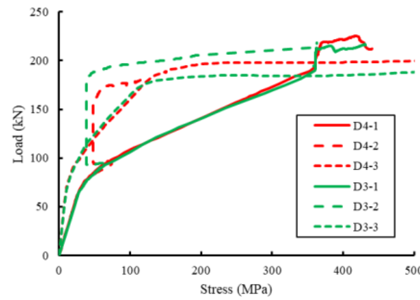
Figure 8. *Load – tension stress of main reinforcement*

3.5. Tension stress of the reinforcement in the form work

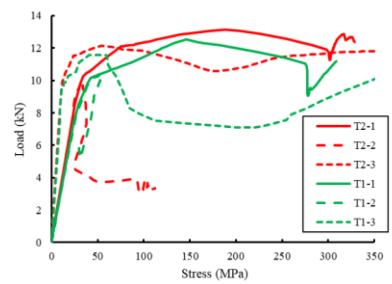
Figure 9 shows the relationship between the load and tensile stress of the reinforcement in the formwork panel installed underneath the components. Figure 9(a) illustrates that the stress in the stainless steel reinforcement grid (C-1, 2 and D-1, 2) tends to develop earlier than that of the FRP reinforcement grid (C-3 and D-3). This is due to the fact that the elastic modulus of FRP is 70 GPa, which is three times smaller than the steel value of 210 GPa. In other words, the steel grid will contribute to bearing tensile loads earlier than the FRP grid during the initial loading phase. This phenomenon also explains why the specimens using stainless steel have a higher ultimate load compared to those using FRP reinforcement grid. However, it should be noted that since the tensile strength of FRP (approximately above 1000 MPa) is much higher than that of ordinary steel, which is 300 MPa, the FRP grid can be more effective in enhancing the flexural capacity of the component after the steel reaches its yield limit. Furthermore, Figure 9(a) shows that after the debonding between the formwork and cast-in-place concrete at a load near 100 kN, the stainless steel in the formwork hardly increases in stress until it approaches the ultimate load. This means that, when the bond with the cast-in-place concrete is lost, the reinforcement inside the formwork contributes little to improving the flexural capacity of the component.

However, the increase in stress of the stainless steel after the load reaches near the ultimate value indicates that it contributes to some extent in limiting the brittle failure of the component.

Additionally, Figure 9(b) also shows similar trends, including the tendency for the stress in the stainless steel reinforcement grid to develop earlier than that in the FRP reinforcement grid, and that the stress in the stainless steel does not increase after the formwork loses its bond with the cast-in-place concrete at a load of around 9 kN. Thus, it can be seen that the reinforcement inside the formwork only contributes to enhancing the flexural resistance when the bond between the formwork and the cast-in-place concrete is intact. However, when the debonding occurs, the reinforcement can also play a role in preventing brittle failure of the component.



(a) Column and beam



(b) Wall and slab

Figure 9. *Relationship between the load and the tension stress of the reinforcement of the formwork*

4. Conclusions

To clarify (i) the flexural behavior of different types of structural components, including columns, beams, walls, and slabs when using the permanent formwork system, (ii) the impact of reinforcement grid in the formwork, and (iii) the bond between the formwork and the cast-in-place concrete, the study conducted a series of FEM analysis with various models of formwork configurations. Some conclusions drawn from the study are as follows:

(1) Permanent formwork significantly enhances the flexural performance of components, including increasing the ultimate load, significantly delaying the onset of cracks, and postponing the yield of the main reinforcement.

(2) The effectiveness mentioned in (1) is more pronounced in thinner components such as walls and slabs compared to columns and beams. This is because, with the same formwork size, the larger the ratio of the formwork size to the cast-in-place concrete, the greater the effect in improving the flexural performance of the component, and vice versa.

(3) The effectiveness in (1) is only ensured when the bond between the formwork and the cast-in-place concrete

is maintained. After the debonding, the formwork no longer participates in bearing loads with the component and thus does not improve the component's flexural performance. Therefore, considering the surface configuration of the formwork to enhance bonding with the cast-in-place concrete is key to the application of the formwork system.

(4) Both stainless steel and non-metallic FRP grid can be used as reinforcement in the formwork structure. Due to its higher elastic modulus, steel mesh may be more effective than FRP grid until yielding occurs. However, for components with large deformations, FRP is also a good method due to its significantly higher tensile strength compared to steel.

Although the study clarified trends in the flexural behavior of different types of components when using the permanent formwork system through numerical analysis, certain limitations remain within the scope of this study. First, experimental studies on components need to be conducted and compared with numerical analysis results to improve the reliability of the findings. Second, the study did not quantitatively analyze the economic aspects of using the formwork system. Additionally, load types that cause shear failure or environmental impacts were not analyzed in this study. Therefore, to move towards widespread application of the formwork system in practice, these issues need further investigation in subsequent stages.

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