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Study on Solutions for Early Dismantling of Aluminum Formwork Systems in High-Rise Building Construction

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Abstract

This paper evaluated the impact of early aluminum formwork (AF) removal on the structural integrity of reinforced concrete (RC) beam-slab systems, specifically focusing on punching shear capacity, deflection, and crack width. The study provided a comprehensive analysis of the AF system, detailing its erection and dismantling sequences while examining its advantages and disadvantages. Moreover, safety principles for early formwork removal were proposed in accordance with the Vietnamese code (TCVN 5574:2018). By utilizing calculation examples based on actual high-rise building constructions and employing the finite element method, the study offered practical guidelines for the safe and effective use of AF systems, balancing rapid construction with structural safety. The findings emphasized the importance of assessing punching shear, deflection, and crack width criteria at the time of formwork removal to ensure structural safety. Results indicated that RC beam-slab systems remain safe in terms of punching shear capacity, deflection, and crack width if the shoring span does not exceed 1.6m when the concrete reaches its design strength. Furthermore, early removal of AF was feasible when the concrete achieved a strength grade of B12.5, with a shoring span of up to 1.6 m and a minimum slab thickness of 200mm. This study also contributed novel insights into optimizing construction efficiency by offering practical guidelines for the safe and effective use of AF systems, thus providing valuable recommendations for construction professionals and engineers.

Keywords: Aluminum Formwork; Aluminum Shuttering; Concrete Construction; Shaped Formwork; Formwork System.

1. Introduction

Aluminum formwork (AF) is increasingly used in high-rise building construction in Vietnam and other countries due to its numerous advantages. Several preliminary studies have been conducted on the characteristics and preliminary calculations of AF. For instance, Dao & Vo [1] have indicated that AF improves quality, ensures safety, and reduces construction time by approximately 20-30% compared to traditional formwork. The popularity of AF is growing in construction projects in Vietnam, as it can reduce construction costs and help minimize environmental impact since most of its waste can be reused. Nguyen [2] has proposed several solutions to advance the use of AF in Vietnam. These include improving regulations to establish a clear legal framework, setting design requirements to ensure quality and safety, and adopting construction methods that optimize performance and minimize risks. Nguyen [2] also emphasized the importance of the AF process in accelerating project timelines, reducing costs, ensuring quality, and protecting the environment by maximizing material use and minimizing waste. La [3] conducted an analysis of AF usage in Vietnam, emphasizing its advantages, including its simple structure, ease of construction, rapid progress, and high safety

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standards. Additionally, AF produces aesthetically pleasing concrete that satisfies consumer and societal expectations. However, the construction process is associated with a significant material loss rate of approximately 20%, necessitating additional investment when transitioning between projects. The high investment cost of AF is compounded by its reliance on materials sourced from foreign suppliers, which limits the use of traditional formwork resources. La [3] also provided a comprehensive examination of the structure and operational aspects of AF, identifying limitations that must be addressed for its effective application in construction. Kieu et al. [4] studied the distribution of construction loads and strength development in reinforced concrete (RC) structures, using Vietnamese and ACI 347.2R-05 standards. This research proposed a procedure for shoring and reshoring formwork systems, focusing on optimal timing for stripping and reshoring. The study also validated the safety and quality of the construction process, offered methods to shorten construction schedules and reduce costs, and recommended using higher-grade concrete, fast-setting additives, advanced formwork technology like AF, and suitable slab and column systems to minimize support time. Moreover, Pham et al. [5] outlined the basic characteristics, advantages, and disadvantages of AF. Based on these insights, a construction process for the erection, dismantling, and necessary precautions for using AF was proposed. Pham et al. [5] also suggested a procedure for calculating and inspecting AF for load-bearing structural systems in high-rise buildings.

In addition, some international standards have addressed various requirements for aluminum and other material formwork, such as Devi & Yadav [6], Yudina et al. [7], Rivaldo and Putra [8], Apdeni et al. [9], Nilimaa et al. [10], Vietnamese code (TCVN 4453:1995) [11], ACI 347-04 "*Guide to Formwork for Concrete*" [12], OSHA (1926) Subpart Q "*Concrete and Masonry Construction*" – Regulations by the Occupational Safety and Health Administration (OSHA) [13]) mentioned that the full load should only be applied to structures after formwork and scaffolding have been removed, once the concrete has reached its design strength. TCVN 4453:1995 [11] specified that for slabs, beams, and arches with spans less than 2 meters, from 2 meters to 8 meters, and greater than 8 meters, formwork removal is permitted when the concrete has reached 50%, 70%, and 90% of its 28-day design strength (R_{28}), respectively. ACI 347-04 "*Guide to Formwork for Concrete*" [12] stated that formwork for walls and columns can be removed after 24 to 48 hours. For slabs, the formwork can be removed after 3 to 4 days, provided that the shores are left in place. The undersides of slabs, with shores still in place, can be removed after one week. Shores supporting slabs less than 15 feet high can be removed after one week, while shores supporting slabs over 15 feet high can be removed after two weeks. Shores supporting beams and arches less than 20 feet high can be removed after two weeks, and shores supporting beams and arches over 20 feet high can be removed after three weeks. OSHA (1926) Subpart Q [13] outlined safety requirements for concrete and formwork construction. These regulations provide guidelines for the design, inspection, and removal of formwork to ensure worker safety. ACI SP-4 [9] – The American Concrete Institute's handbook offered comprehensive information on various types of formworks, as well as design and removal procedures, serving as a crucial reference for engineers and contractors involved in concrete construction.

It is evident that the existing studies and codes have not comprehensively addressed the characteristics (details, advantages, and disadvantages), design processes, assembly and dismantling procedures, and necessary considerations for the AF system. Specifically, the calculation of early AF removal while ensuring structural safety has not been thoroughly investigated. Therefore, this paper provides a detailed analysis of the structure and characteristics of the AF system and proposes a calculation and verification process for early AF removal. Additionally, the study explores the relationship between shoring span, concrete strength, and slab thickness to ensure the early removal of the slab-beam formwork system while meeting requirements for load-bearing capacity, punching shear, deflection, and cracking.

2. Details, Advantages, and Disadvantages of AF

AF basically consists of several main components as follows [5]:

- Aluminum frame: this is the primary component that forms the structure of the formwork, made from aluminum alloy known for its lightweight, durability, corrosion resistance, and high load-bearing capacity. The aluminum frame can be designed in various sizes and shapes according to project requirements.
- Formwork surface: this is the part that directly contacts the concrete, usually made from aluminum or coated with a special layer of aluminum to create a smooth surface. This facilitates easy formwork removal after casting and results in a flat and beautiful concrete surface.
- Connection system: includes components such as bolts, screws, formwork locks, etc., which connect the formwork panels to form a sturdy formwork unit. This system also allows for flexible adjustment of the formwork size and shape.

Bracing and supporting accessories: aluminum or steel bracing bars are used to reinforce the formwork, especially for larger-sized formwork. Additionally, there are other supporting accessories such as base plates, supports, etc., to keep the formwork stable on the ground or elevate it.

Drawing on information provided by manufacturers and various studies conducted both in Vietnam and globally, the prominent advantages of AF are as follows:

- Lightweight and less affected by environmental factors compared to other types of formworks.
- Simple and easy assembly and disassembly process, allowing workers to quickly adapt and saving construction time.
- High recyclability, estimated to recover at least 20% of the initial value.
- Moderate maintenance costs compared to other types of formworks.
- Beautiful concrete surface quality, easy to clean.
- Fast and specialized construction progress. After pouring concrete, it can be dismantled within 48 to 72 hours and reused over 100 times. Some formwork panels and components can be removed in advance, reducing the number of panels needed in high-rise construction.

However, AF also presents several disadvantages:

- High cost, requiring a significant initial investment.
- The positions of the components in the system are fixed, making replacement when damaged quite complex and costly.
- Maintenance after dismantling the formwork requires effort and cost.

3. Verification of RC Beam-Slab System at the Time of AF Removal

3.1. RC Slab

The unique structure of the AF system permits the early removal of various components, including formwork panels, edge-, intermediate-, and end-beams, while leaving the shoring columns either entirely or partially in place (Figure 1). This allows the construction team to efficiently reuse the formwork for subsequent floors. The challenge lies in ensuring that, after the early removal of formwork panels and supporting beams, the remaining shoring column system can adequately support the beam-slab system, maintaining the necessary criteria for load-bearing capacity (moment and shear), punching shear, cracking, and deflection.

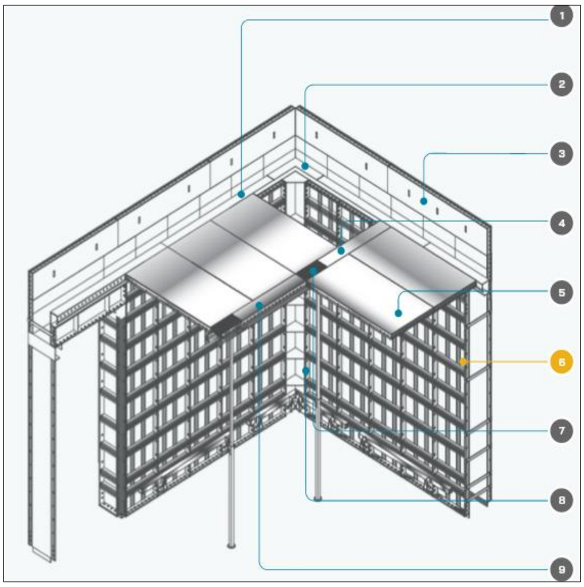


Figure 1. Structure of the AF system; (1): Edge beam; (2): Corner brace; (3): Barrier panel; (4): End beam; (5): Formwork face panel; (6): Formwork wall panel; (7): Shoring head; (8): Wall corner panel; (9): Intermediate beam

Moment and shear capacity verification:

At the time of early removal of formwork panels (leaving only shoring columns), it is necessary to assess the moment and shear capacity of the RC slab. Assuming a 1-meter-wide strip is cut out, and the RC slab is considered as a continuous beam. Then, it is checked for its moment and shear force capacities corresponding to the concrete strength at the time of formwork removal. The loads acting on the RC slab at this stage include the self-weight of the RC slab, other dead loads, and construction live loads (weight of personnel and equipment on formwork system). The criteria for checking moment and shear force capacities according to TCVN 5574:2018 [14] are presented in Equations 1 and 2.

$$M \leq M_{gh} = R_b bx(h_0 - x/2) \tag{1}$$

$$Q \leq Q_b + Q_{sw} = (\varphi_{b2}\, R_{bt}\, bh_0^2)/C + \varphi_{sw} q_{sw} C \tag{2}$$

where $b, h, h_0 = h - a$ are the width, height, and effective height of the section, a is the distance from the centroid of the tension steel to the tension face of the section; R_b, R_{bt} are the calculated compressive and tensile strengths of concrete; x is the height of the compression zone; $\varphi_{b2} = 1.5$ is the coefficient accounting for the influence of longitudinal reinforcement, bond stress, and stress state characteristics of concrete above the inclined crack; $\varphi_{sw} = 0.75$ is the coefficient considering the decrease of internal forces along the length of the inclined crack projection C; $q_{sw} = R_{sw}A_{sw}/s_w$ is the force in the horizontal reinforcement per unit length of the member; C is the projection of the inclined crack on the member axis.

Punching shear verification:

The shoring column transfers the load to the slab through a shoring head with dimensions of 150 mm × 300 mm. This load transfer mechanism can induce a punching shear phenomenon in the slab. This phenomenon is depicted through a punching shear cone with a 45-degree angle, as illustrated in Figure 2 [15–22]. The punching shear cone, which features both a smaller base and a larger base, has dimensions corresponding to 150×300 mm for the smaller base and $(B \times A)mm$ for the larger base, where $A = 300 + h_0$, $B = 150 + h_0$ ($h_0 = h - a$ is the effective height of the slab). This geometric configuration highlights the critical areas for evaluating the punching shear capacity of the slab, ensuring it can safely carry the applied loads without failure.

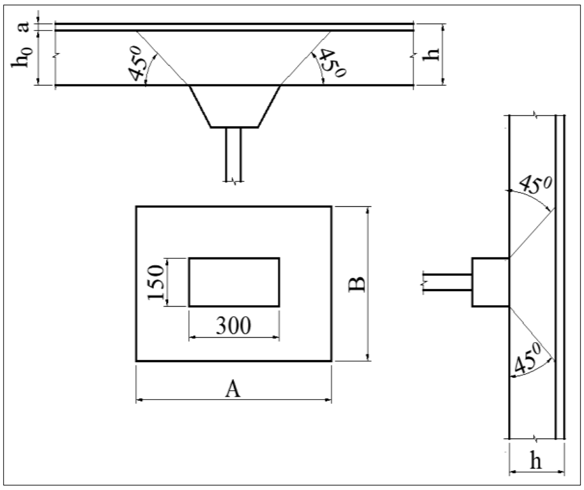


Figure 2. Punching shear cone. Note: All dimensions are in millimeters

According to the Vietnamese design standards for concrete and reinforced concrete structures (TCVN 5574:2018) [14], the punching shear criterion is expressed by Equation 3. If the punching shear criterion is not met, it is necessary to either increase the size of the shoring head or enhance the tensile strength of the concrete slab. Among these options, enlarging the shoring head is generally more effective than the other alternatives for addressing the issue.

$$Q \leq F_{cx} = R_{bt} S_m;\ S_m = 0.5(u_1 + u_2)h_0 \tag{3}$$

where Q is the maximum shear force at the punching shear calculation position; S_m is the area of the punching shear cone; $u_1 = 2(a + b)$, $u_2 = 2(A + B)$.

Crack verification:

Cracking is evaluated using Equation 4, based on the maximum moment occurring in the slab and the cracking resistance moment.

$$M \leq M_{cr} = W_{pl} R_{bt,ser} \pm N e_x \tag{4}$$

where M, M_{cr} are the moment and cracking moment of the section; $W_{pl} = \gamma W_{red}$ is the elastic moment resistance of the section for the outermost concrete layer under tension; $e_x = W_{red}/A_{red}$ is the distance from the point of application of the axial force N (located at the centroid of the converted section of the member) to the core point further away than the tension zone where the crack formation needs to be checked; W_{red} is the elastic moment resistance of the converted section for the tension zone of the section, $W_{red} = I_{red}/y_t$; Where I_{red} is the moment of inertia of the converted section of the member about its centroid, $I_{red} = I + \alpha I_s + \alpha I'_s$; I, I_s, I'_s are the moment of inertia of the concrete section, the steel reinforcement section under tension, and the steel reinforcement section under compression, respectively; $A_{red} = A + \alpha A_s + \alpha A'_s$; A, A_s, A'_s are the cross-sectional areas of concrete, steel reinforcement under tension, and steel reinforcement under compression, respectively; $\alpha = E_s/E_b$ is the conversion factor of steel to concrete; $y_t = S_{t,red}/A_{red}$, where $S_{t,red}$ is the static moment of the converted section of the member about the outermost concrete layer under tension.

Deflection verification:

Deflection (f) is evaluated using the curvature (r) of the structure while neglecting the long-term effects of loading, as outlined in Equation 5.

$$f \leq [f] = 1/r = (1/r)_1 + (1/r)_2 \tag{5}$$

where $(1/r)_1, (1/r)_2$ are respectively the curvature due to the short-term effect of the total load and the short-term effect of the frequent and temporary load. Here, in the calculation and checking at the construction time. The curvature is determined as $(1/r) = M/D$; Where $D = E_{b1} I_{red}$ is the flexural stiffness of the converted cross-sectional area, E_{b1} is the modulus of deformation of concrete under compression (determined depending on the duration of load action).

3.2. RC Beam

Moment resistance verification:

According to TCVN 5574:2018 [14], the RC beam is analyzed as a rectangular section with double reinforcement, and its moment resistance is evaluated using Equations 6 and 7.

$$M \leq M_{gh} = R_b b x (h_0 - 0.5x) + R_{sc} A'_s (h_0 - a') \tag{6}$$

$$x = (R_s A_S - R_{sc} A'_s)/(R_b b) \tag{7}$$

where R_{sc}, A'_s are the design strength and cross-sectional area of the longitudinal reinforcement under compression; a' is the distance from the centroid of the compression reinforcement to the compression edge.

Other requirement verification:

The criteria for checking shear capacity, cracks, and deflection are performed similarly to those of the RC slab.

4. Examples of Verification for RC Beam–Slab System at the Time of AF Removal

4.1. Verification of RC Slab

Using information from the ASIANA construction project [23] currently underway in Da Nang, Vietnam, verify the RC beam-slab system at the time of formwork removal with the following details: Slab size of 8 m × 8 m, concrete grade B50 with compressive strength $R_b = 36\,MPa$; reinforcing steel grade CB500V with yield strength $R_s = R_{sc} = 435\,MPa$; slab thickness of 150 mm; beam cross-section dimension of 400 mm × 600 mm; concrete cover of 40 mm, top layer reinforcement of $\phi 14@200$; bottom layer reinforcement of $\phi 12@100$; and spacing of supporting columns in two directions of 1.2 m. The early removal check of the formwork slab is required to ensure the concrete reaches a minimum strength. Let's assume the early removal check is conducted when the concrete strength reaches B15 ($R_b = 7.5\,MPa$; $R_{bt} = 0.66\,MPa$; $R_{bn} = 1.0\,MPa$; $E_b = 21000\,MPa$).

The applied load on the slab includes the weight of the RC slab, other static loads, and construction loads, as detailed in Table 1. The calculated load value is converted into a concentrated force of $Q = 15.28 \times 1.44 = 22.00\,kN$, with the transmitted area determined as $A_{cal} = 1.2$ m × 1.2 m $= 1.44\,m^2$.

Table 1. Applied loads on RC slab

Load type	Thickness (mm)	Value (kN/m^2)	Factor	Factored value (kN/m^2)
RC slab weight		3.80	1.1	4.13
Other dead loads	150	2.00	1.2	2.40
Construction loads		2.50	1.3	3.25
Total				**9.78**

To determine internal forces, the floor strip with a width of $1.2m$ is considered as a beam with two pinned ends for safety. According to structural mechanics theory, the moment at the midpoint and the supports are given by $M_n = M_g = ql^2/12$. However, the assumed pinned connection at both ends is not suitable for the actual structures. Therefore, to ensure safety, the moment at the supports and midpoint is taken as the maximum moment of a simple beam with two pinned supports: $M_n = M_g = ql^2/8 = 3.30\ kNm$ (where $q = q' \times 1.2\ m$).

Moment capacity verification:

Since the slab has been designed to ensure moment resistance, the moment capacity verification of the slab is conducted by checking the reinforcement ratio of the slab. According to the regulations of TCVN 5574:2018 [14], the minimum steel reinforcement ratio is $\mu_{min} = 0.05\%$, and the maximum steel reinforcement ratio is $\mu_{max} = \xi_R R_b / R_s \times 100\% = 0.011\%$. The steel reinforcement ratio in the slab is $\mu = A_s / bh_0 \times 100\%$. The check results are shown in Table 2.

Table 2. Steel reinforcement ratio verification

Position	$b\ (mm)$	$\phi\ (mm)$	$h_0\ (mm)$	$M\ (kNm)$	$A_{s,cal}\ (mm2)$	Choose	$A_s\ (mm2)$	μ (%)	Check
Span	1200	12	120	2.11	24.5	$\phi 12@100$	1357	0.365	Ok
Support	1200	14	120	2.11	24.5	$\phi 14@200$	924	0.248	Ok

Note: b, h_0 represent the width and effective depth of the section; M is the maximum calculated moment; $A_{s,cal}$, A_s denote the calculated and provided area of reinforcement, respectively; μ is the reinforcement ratio.

Shear capacity verification (punching shear at the column head):

The punching shear capacity at the column head is evaluated using Equation 3. As shown in Table 3, the punching shear resistance of the RC slab is $F_{cx} = 90\ kN$, which exceeds the maximum shear force at the column head, measured at $14.8\ kN$

Table 3. Verification of punching shear capacity

$h_0\ (mm)$	$a\ (mm)$	$b\ (mm)$	$A\ (mm)$	$B\ (mm)$	$u_1\ (mm)$	$u_2\ (mm)$	$S_m\ (mm)$	$R_{bt}\ (Mpa)$	$F_{cx}\ (kN)$	$Q(kN)$	Check
120	150	300	270	420	900	1380	136800	0.66	90.0	14.8	Ok

Note: $A, B, u_1, u_2, S_m, F_{cx}$ are determined according to Equation 3; Q is the shear force at the head of the supporting column (the location for punching shear check).

Crack verification:

Verify crack formation using Equation 9. As specified in TCVN 5574:2018 [14], the permissible crack width for RC structures is set at 0.4mm to ensure structural integrity and durability. The assessment involves calculating the actual crack width and comparing it against this threshold. The detailed verification results, including the computed crack widths and corresponding safety margins, are presented in Tables 4 and 5, providing a comprehensive evaluation of the slab's performance under the applied loading conditions.

Table 4. Parameters for crack verification

Position	$E_s\ (MPa)$	$E_b\ (MPa)$	α	$A_{red}\ (mm^2)$	$S_{t,red}\ (mm^3)$	y_t	n	n'	$N\ (kN)$	γ
Span	2.00×10^5	2.1×10^4	9.52	201724	1.53×10^7	75.9	12	6	0	1.3
Support	2.00×10^5	2.1×10^4	9.52	201724	1.49×10^7	74.1	6	12	0	1.3

Note: n, n' are the number of steel bars in the tension and compression zones; N is the axial force; $y_t = S_{t,red}/A_{red}$, $A_{red} = bh + \alpha(A_s + A_s')$, $S_{t,red} = 0.5bh^2 + \alpha(A_s h_0 + A_s' a')$.

Table 5. Slab crack verification

Position	$I\ (mm^4)$	$I_s\ (mm^4)$	$I_s'\ (mm^4)$	$I_{red}\ (mm^4)$	$W_{red}\ (mm^3)$	$W_{pl}\ (mm^3)$	$R_{b,ser}\ (MPa)$	$M_{cr}\ (kNm)$	$M\ (kNm)$	Check
Span	$3{,}38 \times 10^8$	$3{,}16 \times 10^7$	$1{,}17 \times 10^7$	$7{,}5 \times 10^8$	$0{,}99 \times 10^7$	$1{,}28 \times 10^7$	1,0	12,85	2,11	Not crack
Support	$3{,}38 \times 10^8$	$1{,}17 \times 10^7$	$3{,}16 \times 10^7$	$7{,}5 \times 10^8$	$1{,}01 \times 10^7$	$1{,}32 \times 10^7$	1,0	13,17	2,11	Not crack

Note: the coefficients in the table above are taken from TCVN 5574:2018 [14]; $I = bh^3/12$; $I_s = [0{,}1D^4 + (h_0 - y_t)^2 A_s n]$; $I_{red} = I + \alpha I_s'$; $W_{red} = I_{red}/y_t$; $W_{pl} = \gamma W_{red}$; $M_{cr} = W_{pl} R_{bt,ser} + N$

Verification of deflection:

According to TCVN 5574:2018 [14], the deflection of the floor is assessed using Equation 10. The calculated deflection is then compared to the permissible deflection, $[f] = 1/250L$, and the results are presented in Table 6.

Table 6. Slab deflection verification

$E_{bl}\ (MPa)$	α	$I_{red}\ (mm^4)$	D	$(1/r)_1$	$E_{bt}\ (MPa)$	α	$I_{red}\ (mm^4)$	D'	$(1/r)_2$	$1/r$	s	$f\ (mm)$	$[f]\ (mm)$	Check
17850	11.2	8.23×10^8	1.47×10^8	4.78×10^{-8}	5833.3	34.3	1.82×10^9	1.06×10^{13}	1.99×10^{-7}	2.46×10^{-7}	0.104	0.04	4.8	Ok

Note: the coefficients in the table above are taken from TCVN 5574:2018 [14]; $E_{bl} = 0{,}85 E_b$; $D = E_{bl} I_{red}$; $E_{bt} = E_b/(1 - \varphi_{b,cr})$, $\varphi_{b,cr} = 2{,}6$; $D' = E_{bt} I_{red}$; $f = sL^2(1/r)$; $[f] = 1/250L$

4.2. RC Beam

Based on the parameters outlined in Section 4.1, the reinforcement for both the top and bottom of the beam consists of $5\phi22$. The props are spaced 0.9 m apart along the length of the beam, with an additional spacing of 1.2 m on either side of the beam. To ensure structural integrity, an assessment of the early removal of the beam formwork is necessary. In alignment with the assumptions applied to the slab formwork, it is considered that at the time of early removal, the concrete will have achieved a strength grade of B15. The loads applied to the beam include the weight of the RC slab and beam, as well as other dead and live construction loads. These loads are comprehensively detailed in Table 7. To convert these loads into a concentrated force, the total load is calculated as $Q = qA_{cal} = 15.51\ kN$, where the load transmission area $A_{cal} = 0.9\text{ m} \times 1.2\text{ m} = 1.08\ m^2$.

Table 7. Applied loads on RC beam

Load type	Thickness (mm)	Value (kN/m^2)	Factor	Factored value (kN/m^2)
RC slab weight	150	3.8	1.1	4.13
RC beam weight (excluding slab weight)		11.3	1.1	12.38
Other dead loads	450	2.0	1.2	2.40
Construction loads		2.5	1.3	3.25
Total				**22.15**

Determination of internal forces:

Similar to the slab, for safety purposes, the internal force for verification is considered as $M_n = M_g = ql^2/8 = 1.74\ kNm$, where $l = 0.9\ m$ represents the spacing between the beam props.

Moment capacity verification: Similar to the slab, the moment capacity of the beam is assessed based on the designed reinforcement ratio in accordance with TCVN 5574:2018 [14]. The steel ratio is compared against the minimum steel ratio (μ_{min}) and the maximum steel ratio (μ_{max}). The results of this verification are presented in Table 8.

Table 8. Verification of beam steel ratio

Position	$b\ (mm)$	$h_0\ (mm)$	$M\ (kNm)$	$A_{s,cal}\ (mm^2)$	Choose	$A_s\ (mm^2)$	μ (%)	μ_{min} (%)	μ_{max} (%)	Check
Span	400	560	1.74	7.2	$5\phi22$	1901	0.85	0.05	1.09	Ok
Support	400	560	1.74	7.2	$5\phi22$	1901	0.85	0.05	1.09	Ok

Shear capacity verification:

In accordance with TCVN 5574:2018 [14], the shear capacity of the beam is evaluated using a similar approach to that applied for the slab. The detailed results of this shear capacity verification, including all relevant calculations and comparisons, are systematically presented in Table 9.

Table 9. Shear capacity check of the beam

φ_{w1}	φ_{b1}	$b\ (mm)$	$h\ (mm)$	$a\ (mm)$	$h_0\ (mm)$	$R_{bt}\ (MPa)$	$Q_{bt}\ (kN)$	$Q_A\ (kN)$	Check
1	1	400	600	40	560	0.66	44.4	8.6	Ok

Note: φ_{w1} is the factor accounting for the influence of transverse reinforcement perpendicular to the axis of the structural member; φ_{b1} is the factor accounting for the ability to redistribute internal forces for different types of concrete; $Q_{bt} = 0.3\varphi_{w1}\varphi_{b1}R_{bt}bh_0$; R_{bt} is the design tensile strength of concrete; Q_A is the maximum shear force in the beam.

Crack verification:

In accordance with TCVN 5574:2018 [14], the evaluation of crack formation in the beam is conducted using the same method applied to the slab, specifically through the use of Equation 10. This assessment considers the beam's susceptibility to cracking under the given load conditions. The comprehensive results of this crack formation analysis are presented in Tables 10 and 11, which detail the calculated crack widths and their comparison against allowable limits.

Table 10. Calculation parameters for cracks in the beam

Position	$E_s\ (MPa)$	$E_b\ (MPa)$	α	$A_{red}\ (mm^2)$	$S_{t,red}\ (mm^3)$	y_t	n	n'	$N (kN)$	γ
Span	200000	21000	9.52	276203	8.29×10^7	300	12	6	0	1.3
Support	200000	21000	9.52	276203	8.29×10^7	300	6	12	0	1.3

Note: n, n' are the number of reinforcing bars in the tensile and compressive regions, respectively; N is axial force; $y_t = S_{t,red}/A_{red}$, $A_{red} = bh + \alpha(A_s + A_s')$, $S_{t,red} = 0.5bh^2 + \alpha(A_s h_0 + A_s' a')$.

Table 11. Assessment of crack formation in the beam

Position	$I\ (mm^4)$	$I_s\ (mm^4)$	$I'_s\ (mm^4)$	$I_{red}\ (mm^4)$	$W_{red}\ (mm^3)$	$W_{pl}\ (mm^3)$	$R_{b,ser}\ (MPa)$	$M_{cr}\ (kNm)$	$M\ (kNm)$	Check
Span	7.2×10^9	1.5×10^9	7.7×10^8	2.9×10^{10}	9.74×10^7	1.3×10^8	1.0	126.7	1.74	Not crack
Support	7.2×10^9	7.7×10^8	1.5×10^9	2.9×10^{10}	9.74×10^7	1.3×10^8	1.0	126.7	1.74	Not crack

Note: the coefficients in the table above are taken from TCVN 5574:2018 [14]; $I = bh^3/12$; $I_s = [0{,}1D^4 + (h_0 - y_t)^2 A_s n]$; $I_{red} = I + \alpha I'_s$; $W_{red} = I_{red}/y_t$; $W_{pl} = \gamma W_{red}$; $M_{cr} = W_{pl} R_{bt,ser} + N$.

Deflection verification:

In a manner consistent with the slab analysis, the deflection of the beam is evaluated using the same criteria. The detailed results of this deflection check are summarized in Table 12, which provides a comparison of the calculated deflection against permissible limits. This assessment ensures that the beam meets the required performance standards for deflection under applied loads.

Table 12. Deflection check of the beam

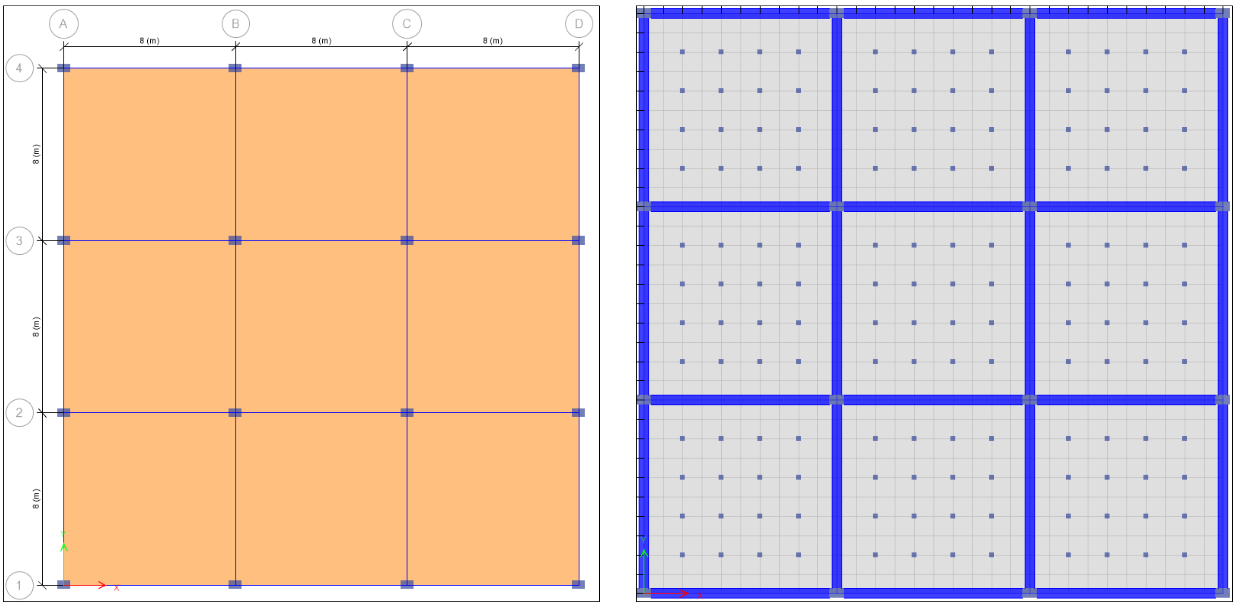
$E_{bl}\ (MPa)$	α	$I_{red}\ (mm^4)$	D	$(1/r)_1$	$E_{bt}\ (MPa)$	α	$I_{red}\ (mm^4)$	D	$(1/r)_2$	$1/r$	s	$f\ (mm)$	$[f]\ (mm)$	Check
17850	11.2	3.3×10^{10}	5.9×10^{14}	2.2×10^{-10}	5833	34.3	8.6×10^{10}	5.1×10^{14}	1.8×10^{-9}	2.0×10^{-9}	0.11	0.0002	3.6	Ok

Note: the coefficients in the table above are taken from TCVN 5574:2018 [14];$\alpha = E_s/E_{bl}$; $E_{bl} = 0{,}85E_b$; $D = E_{bl} I_{red}$; $E_{bt} = E_b/(1 - \varphi_{b,cr})$, $\varphi_{b,cr} = 2{,}6$; $D' = E_{bt} I_{red}$; $f = sL^2(1/r)$; $[f] = 1/250L$

Therefore, it can be observed that upon the removal of all formwork panels, while retaining the system of floor props and beams, the structural system of the slab and beams satisfies the requirements for moment resistance, punching shear capacity, shear strength, deflection limits, and crack width. However, maintaining the props in place throughout the construction process can hinder progress. Consequently, this paper aims to explore and assess the feasibility of partially removing the props, ensuring that the structural integrity is preserved for load-bearing capacities (including moment and shear), deflection criteria, and crack width, in accordance with the relevant standards.

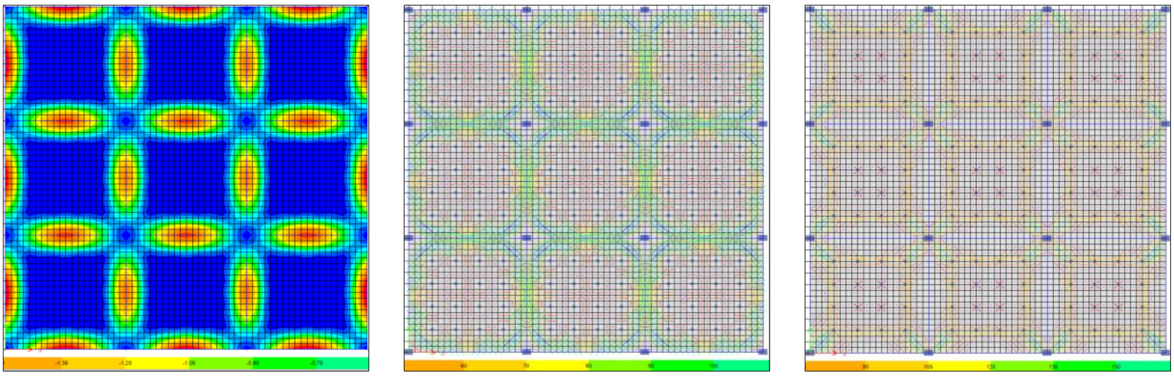
5. The Influence Factors on Early Removal of Beam-Slab Formwork

To examine how factors such as concrete strength, number of support points, and slab thickness affect the load resistance, deflection, and crack width of the RC beam-slab system, this study uses a sample beam-slab system, as depicted in Figure 3. The parameters for the slab and beams are detailed in the example provided in Section 4. The objective is to assess the performance of the beam-slab system under early formwork removal.



(a) Floor Plan (b) Layout of Support Columns

Figure 3. Floor plan and layout of support columns



$\times 10^{1}(mm)$ (a) Deflection

$\times 10^{-3}(mm)$ (b) Cracks on the bottom surface of slab

$\times 10^{-3}(mm)$ (c) Cracks on the top surface of slab

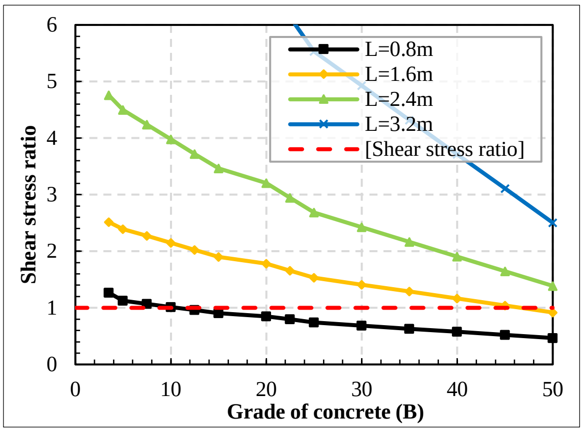
Figure 4. Images of deflection and cracks in the beam-slab system

To investigate and develop solutions for the early removal of beam-slab formwork, the authors employ the finite element method as a comprehensive analytical tool. This method is utilized to assess several critical factors, including punching shear, deflection, and cracking within both the slab and beams. The analysis focuses on the structural performance at the specific stage when the formwork is removed ahead of the conventional schedule. By applying the finite element method, the study aims to provide a detailed understanding of how early formwork removal affects the structural integrity of the beam-slab system, ensuring that safety and performance criteria are met under these adjusted conditions. The results from this analysis will guide the development of practical solutions to optimize formwork removal timing while maintaining the necessary structural support and performance. The calculation results for punching shear, deflection, and crack width, corresponding to shoring column spacings of 0.8 m, 1.6 m, 2.4 m, and 3.2 m, and slab thicknesses of 80 mm, 120 mm, 150 mm, 200 mm, and 300 mm, are illustrated in Figures 5, 6, and 7.

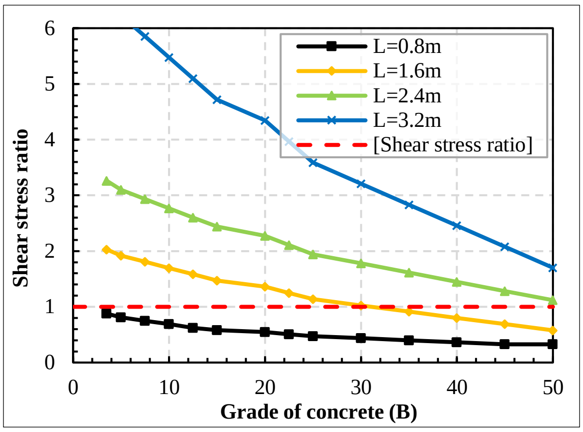
Figure 5 illustrates the relationship between the concrete strength at the time of removal (represented by the strength grade) and the punching shear resistance of the slab (expressed by the shear stress ratio = shear stress / shear capacity) corresponding to different shoring spans ($L = 0.8\ m - 3.2\ m$) and slab thicknesses ($h_s = 80\ mm - 300\ mm$). It can be seen that the slab will not experience punching shear failure if the shear stress ratio is ≤ 1 (the red line in Figure 5 represents the allowable shear stress ratio). Similarly, Figure 7 illustrates the relationship between the concrete strength at the time of removal (represented by the strength grade B) and the allowable crack width ([a_crc]) corresponding to L and h_s. While Figure 6 illustrates the relationship between the deflection ratio (deflection ratio = deflection/span) and h_s corresponding to L (the red line in Figure 6 represents the allowable deflection/span ratio ([f/L]). Some observations drawn from the calculation results shown in Figures 5 to 7 are as follows:

- It is evident that it is crucial to assess the criteria for punching shear, deflection, and crack width at the time of formwork removal to ensure structural safety.
- Increasing the concrete strength improves the slab's punching shear resistance by reducing the shear stress ratio. Concrete strength has a significant impact on the slab's punching shear resistance, while its effect on the deflection and cracking of the beam-slab system is comparatively less pronounced.
- For slab thicknesses exceeding 100 mm, the slab meets deflection requirements for all shoring spans considered in the study ($L = 0.8\ -\ 3.2\ m$).
- The shoring span is less than 3.2 m, crack width satisfied the standard requirement regardless concrete strength.
- It can be observed that when the concrete reaches a design strength of B50, the beam-slab system meets safety requirements for punching shear, deflection, and cracking, provided that the shoring span does not exceed 1.6 m.
- The primary factors influencing the early removal of formwork in the beam-slab system are the concrete strength at the time of removal, the shoring span (distance between shores), and the slab thickness.
- Based on the criteria for punching shear, deflection, and crack width, it can be concluded that early removal of shores is permissible when the concrete strength grade reaches approximately B12.5 with shoring span $L \leq 0.8\ m$. In case of the shoring span L > 0.8 m, it is essential to consider the affecting factors to ensure safety during early formwork removal.
- At the time of early removal (at concrete grade B12.5), when $L \leq 1.6\ m$, the RC beam-slab system would be safe if $h_s \geq 150\ mm$. When $L \leq 2.4\ m$, the RC beam-slab system would be safe if $h_s > 200\ mm$. When $L \leq 3.2\ m$, the RC beam-slab system would be safe if $h_s \geq 300\ mm$. At the different times of formwork removal, it should use Figures 5, 6, and 7 to determine required shoring spans and thicknesses.

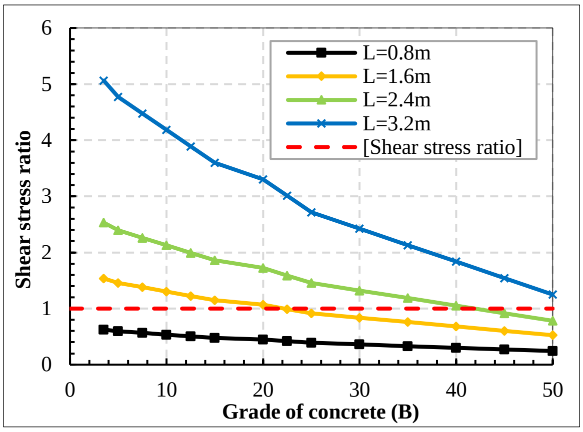
At the early stage of formwork removal (corresponding to a concrete strength grade of B12.5), the RC beam-slab system is considered safe if $L \leq 1.6\ m$ and $h_s \geq 150\ mm$. For shoring spans up to 2.4 m, the beam-slab system is safe if $h_s > 200\ mm$. For shoring spans up to 3.2 m, a minimum slab thickness of 300 mm is required. For other removal time points, Figures 5 to 7 can be used to determine the necessary shoring spans and slab thicknesses.



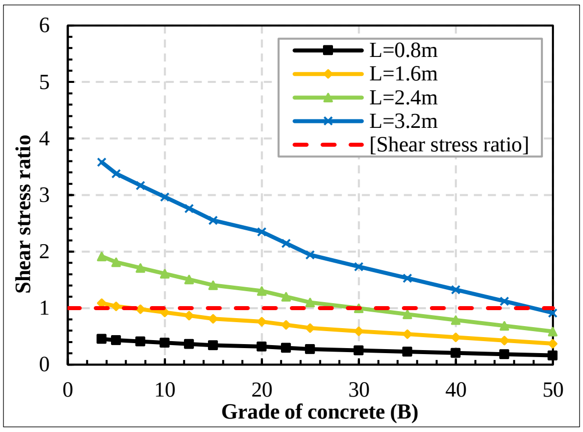
(a) $h_s = 80\ mm$



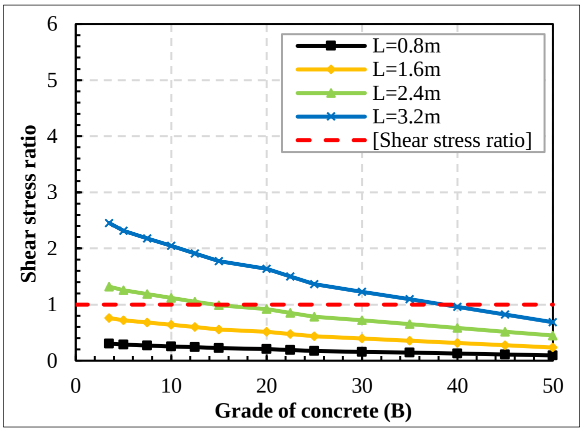
(b) $h_s = 100\ mm$



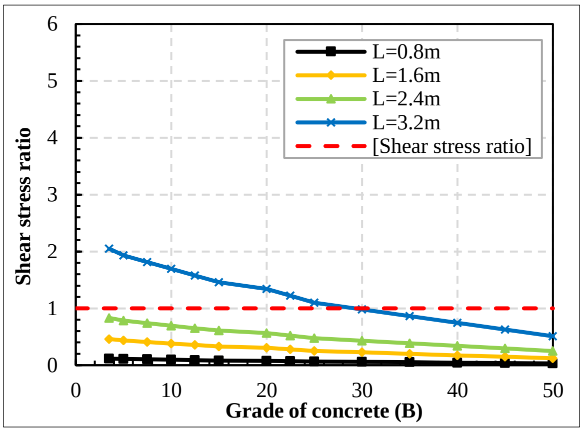
(c) $h_s = 120\ mm$



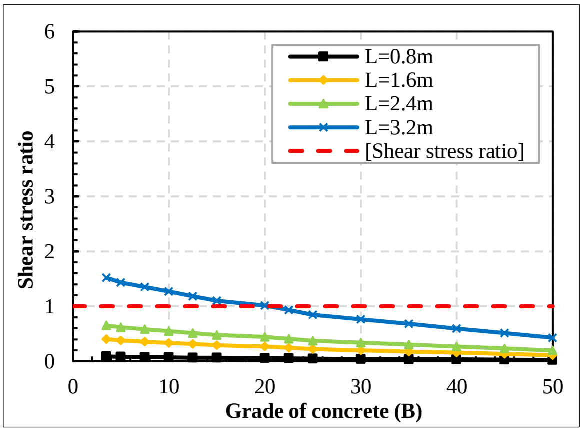
(d) $h_s = 150\ mm$



(e) $h_s = 200\ mm$



(f) $h_s = 300\ mm$



(g) $h_s = 350\ mm$

Figure 5. Relationship between concrete strength and puncture resistance (Note: - Shear stress ratio = maximum shear stress / concrete shear capacity, the design compressive strength of concrete is determined based on the strength grade B according to TCVN 5574:2018 [14]).

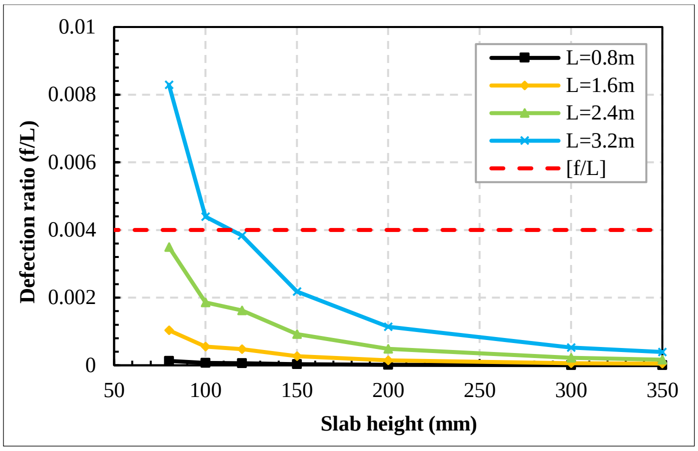
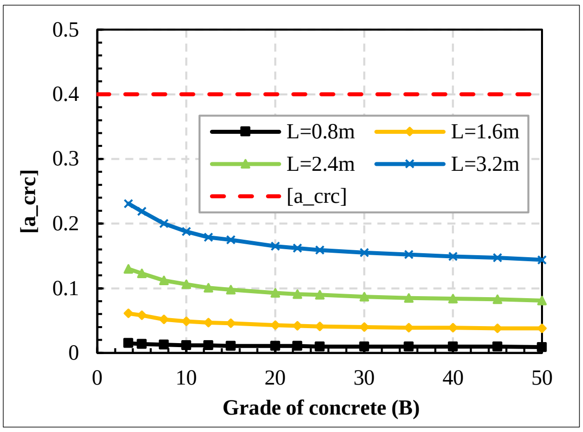
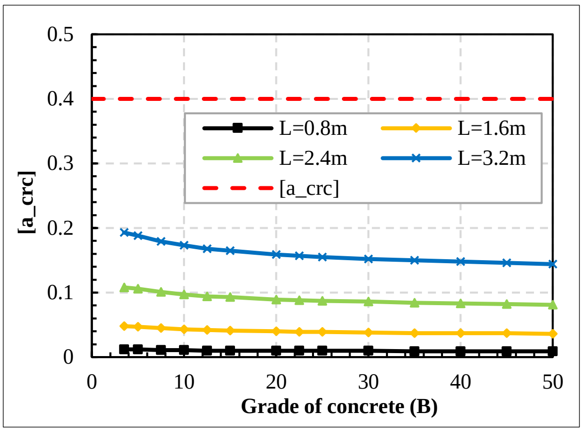


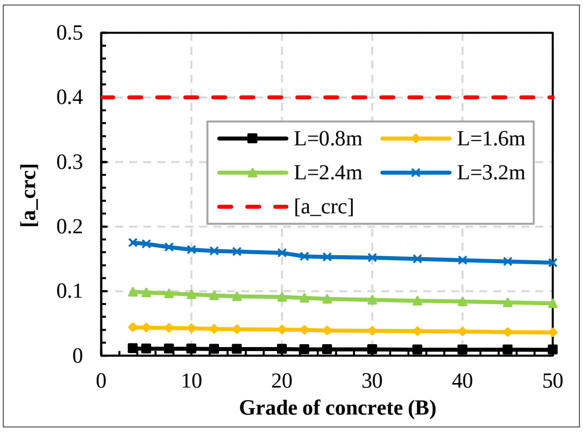
Figure 6. Relationship between deflection ratio and slab thickness. Note: the allowable deflection ratio [*f*/L] = 1/250 = 0.004 based on TCVN 5574: 2018 [14]



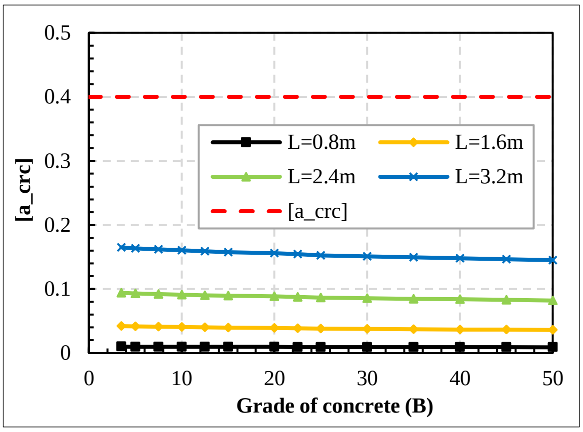
(a) $h_s = 80\ mm$



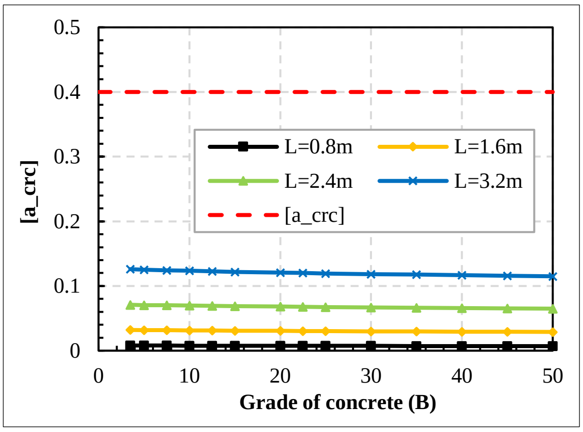
(b) $h_s = 100\ mm$



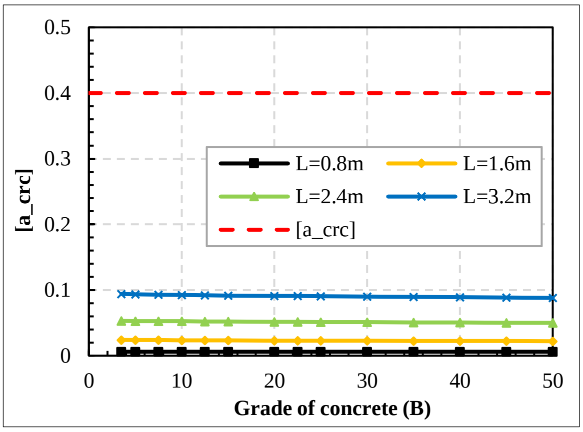
(c) $h_s = 120\ mm$



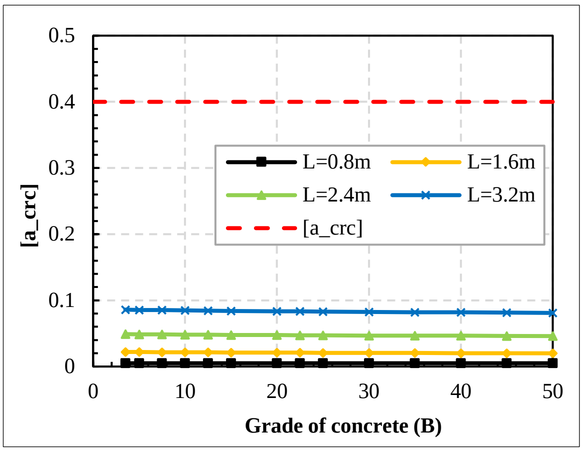
(d) $h_s = 150\ mm$



(e) $h_s = 200\ mm$



(f) $h_s = 300\ mm$



(g) $h_s = 350\ mm$

Figure 7. Relationship between crack width and concrete strength grade. Note: the allowable crack width [a_crc] = 0.4mm based on TCVN 5574: 2018 [14]

The calculations for early formwork removal were applied to the ASIANA project in Da Nang, Vietnam, as shown in Figure 8. It can be seen that appropriate calculations allow for the early removal of formwork and shoring beams, leaving only the supporting columns to ensure the safety of the structural system. This helps accelerate the construction progress, increases the turnover of formwork, and thus reduces the cost of the construction project. Additionally, early removal of some of the shoring columns also helps create a more spacious working area to facilitate subsequent tasks.

(a) The elevation of ASIANA project

(b) Beam-slab formwork system before early formwork removal

(c) Slab formwork system after early formwork removal

(d) Beam formwork system after early formwork removal

Figure 8. Application of the early formwork removal method for the ASIANA project in Da Nang, Vietnam

6. Proposal for Aluminum Formwork Installation and Removal Procedure

To ensure safety throughout the construction process and during the early removal of the A) system, the authors recommend the following procedures for installation and removal:

Installation Procedure:

Step 1: Preparation and installation of column and wall formwork

- Roughen and clean the bases of columns and walls to ensure proper adhesion and stability.
- Place and secure the steel reinforcement as per design specifications, and conduct a thorough inspection to confirm proper installation.
- Accurately mark the positions and dimensions of columns and walls on the construction site to guide formwork placement.
- Thoroughly clean the surfaces of formwork panels to remove any debris, dust, or residues that may affect the quality of the concrete finish.
- Assemble and install scaffolding as needed to support construction activities and provide access to higher areas.
- Set up and secure the formwork for columns and walls according to the specified design and dimensions, ensuring alignment and stability before proceeding with concrete placement.

Step 2: Beam formwork and props installation

- Gather and prepare all materials required for beam formwork and props, ensuring they meet the specifications and are in good condition.
- Set up scaffolding to provide safe and stable access for installation and construction activities related to the beam formwork.
- Position and secure the beam formwork according to the design requirements, ensuring proper alignment and support for concrete placement.

Step 3: Slab formwork and props installation

- Gather and prepare all necessary materials for slab formwork and props, ensuring they meet the design specifications and are in good condition.
- Set up scaffolding to provide safe and stable access for the installation and construction of the slab formwork.
- Position and secure the slab formwork according to the design requirements, ensuring proper alignment and support for concrete placement.
- After installing the slab formwork, clearly mark the sequence of formwork panels to facilitate easy installation during subsequent floors.

Step 4: Staircase formwork installation

- Gather all necessary materials for staircase formwork, ensuring they meet design specifications and are in proper condition.
- Set up scaffolding to provide safe and stable access for installing the staircase formwork.
- Position and secure the staircase formwork according to the design requirements, ensuring proper alignment and support for concrete placement.

Removal Procedure:

Step 1: Column and wall formwork removal

- After concrete pouring, if concrete reaches 5MPa strength (approximately 8 to 18 hours depending on weather conditions), proceed with column-wall formwork removal.
- The removal area must be cordoned off, and danger signs must be displayed.
- Use specialized formwork removal tools; Do not directly hit formwork panels with a hammer to avoid damage.
- Round and flat pins must be collected to prevent loss.
- Removed formwork panels should be transported to subsequent floors through technical holes or elevator shafts and stacked in designated areas as marked earlier.
- Formwork panels must be cleaned and coated with release oil before installation for the next floor.
- For column-wall formwork systems, upper knicker sets must be retained to support formwork panels for the next floor.

Step 2: Beam-slab formwork removal

- After concrete pouring, if concrete reaches the required strength for early removal, proceed with beam-slab formwork removal.
- Remove the bottom beam formwork and beam sides. Then remove slab ribs (middle beam, end beam) while keeping all prop heads and beam props intact.

All props are retained for 2.5 floors (meaning props and prop heads of the first floor are removed only when construction reaches the fourth floor).

7. Conclusion

The paper provided a comprehensive analysis of the details, advantages, disadvantages, and processes involved in the erection and dismantling of AF systems. By examining practical construction projects, crucial considerations for the erection and dismantling phases are proposed. Additionally, this study suggests a calculation and safety check procedure for beams and slabs during dismantling, supported by practical example calculations for construction projects at both the concrete design strength and during early dismantling. The study investigated the relationship between shoring spans, slab thicknesses, and concrete strength at the time of removal, in relation to punching shear, allowable deflection, and crack width. Key findings highlight the importance of assessing criteria for punching shear, deflection, and crack width at the time of formwork removal to ensure structural safety. This study also notes that increasing concrete strength significantly improves the slab's punching shear resistance by reducing the shear stress ratio, although its effect on deflection and cracking is less pronounced. For slab thicknesses exceeding 100mm, deflection requirements are met for all considered shoring spans ($L = 0.8\ m - 3.2\ m$). When the shoring span is less than 3.2m, the crack width satisfies standard requirements regardless of concrete strength. The beam-slab system meets safety requirements for punching shear, deflection, and cracking when the concrete reaches a design strength, and the shoring span does not exceed 1.6 m.

Furthermore, the primary factors influencing early formwork removal in the beam-slab system include concrete strength at the time of removal, shoring span, and slab thickness. It can be seen that early removal of shores is permissible at a concrete strength grade of B12.5 with a shoring span of $L \leq 0.8\ m$. For shoring spans greater than 0.8 m, additional considerations must be considered to ensure safety. Specifically, at a concrete grade of B12.5, the RC beam-slab system is safe if $L \leq 1.6\ m$ and $h_s \geq 150\ mm$. For shoring spans $L \leq 2.4\ m$, a slab thickness of $h_s > 200\ mm$ is necessary, while for $L \leq 3.2\ m$, a minimum slab thickness of 300 mm is required. Figures 5, 6, and 7 provide guidance on the required shoring spans and slab thicknesses for various times of formwork removal. These conclusions are drawn from the use of conventional concrete without additives. Further research is needed to evaluate the specific effects and performance when using other admixtures in concrete.

8. Declarations

8.1. Author Contributions

Conceptualization, Q.P.; methodology, P.P.; software, P.P.; validation, P.P.; formal analysis, P.P.; investigation, P.P.; resources, Q.P.; data curation, Q.P.; writing—original draft preparation, P.P. and Q.P.; writing—review and editing, P.P. and Q.P.; visualization, P.P. and Q.P.; supervision, P.P.; project administration, P.P. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

8.3. Funding

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8.4. Acknowledgements

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8.5. Conflicts of Interest

The authors declare no conflict of interest.

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