Methodology for determining the parameters of a belt-type formwork module for vertical reinforced concrete structures

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Received: 11.10.2025, accepted: 23.11.2025
https://doi.org/10.32347/st.2025.4.1901

Abstract. The article presents a comprehensive methodology for determining, analysing, and optimizing the parameters of a belt-type formwork module used for constructing vertical reinforced-concrete elements within group mechanized systems. Particular attention is given to the mechanics of interaction between the flexible forming belt and early-age concrete, where the key factor is the tangential separation force governed by the roller diameter, belt width, module height, temperature regime, and concrete strength development kinetics. The proposed analytical model demonstrates that the localized tangential detachment zone formed during module lifting significantly reduces energy consumption, minimizes peak loads on the concrete surface, and decreases the likelihood of defects—advantages that distinctly differentiate belt-type systems from traditional panel formwork.

A mathematical model of the technological flow for a set of formwork modules was developed using mixed-integer linear programming (MILP). This model enables optimization of lifting frequency, the number of active modules, rational roller diameters, and concrete placing intervals while considering production constraints and environmental effects. Variational and statistical simulations, incorporating temperature fluctuations, concrete grades, rheological changes, and stochastic deviations of the technological process, confirmed the system's stable performance under various operating conditions. The graphical results demonstrate a potential 18–35% reduction in concreting duration, a 2–4-fold decrease in separation forces, and a notable increase in formwork turnover.

The findings form a scientific basis for designing next-generation mechanized formwork complexes capable of ensuring higher productivity, improved forming quality, and enhanced adaptability to external conditions. The proposed methodology also creates prerequisites for the development of digital twins of construction processes, the implementation of SCADA-based automated monitoring, and the integration of BIM solutions into the control architecture of group belt-type formwork modules.

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Keywords: group formwork modules, belt formwork, panel formwork, tangential separation, formwork roller, monolithic pylons, technological cycle, optimization, MILP, BIM, SCADA,

monolithic construction technology, concrete hardening, automation of formwork systems.

INTRODUCTION

Modern monolithic construction technologies are characterized by increasing requirements for productivity, controllability and accuracy of the processes of forming vertical reinforced concrete structures. The use of traditional panel formwork systems is accompanied by significant labor costs, high tear-off forces, limitations on the speed of reuse, as well as dependence on climatic conditions and the intensity of concrete hardening.

In response to these challenges, technologies of group mobile formwork modules are actively developing. These systems enable cyclic and safe formation of pylons based on a modular principle. A key feature of such systems is the use of a flexible forming element that detaches tangentially from the concrete surface at the lower part of the module. This fundamentally changes the mechanics of the formwork–concrete interaction, reduces energy consumption, improves surface quality, and increases formwork turnover.

However, until now there has been no scientifically grounded methodology for determining the optimal roller diameter—an essential component of the module that governs:

- the detachment force of the belt from the concrete surface;
- allowable limits of lifting acceleration;
- the quality of the formed concrete surface;
- technological stability of the cycle with varying temperatures and hardening rates.

To ensure safe and automated operation of modules, it is necessary to develop a scientifically sound approach that would take into account:

- the physics of forming tape bending;
- lifting kinematics;
- dependence of concrete strength on temperature;
- adhesion characteristics of the surface;
- production variability of conditions (through statistical modeling).

All these factors substantiate the relevance of this study and confirm the need for a unified methodology to determine the parameters of mobile formwork modules.

Goal To develop a comprehensive engineering methodology for determining the optimal roller diameter of the forming element in modular vertical formwork, taking into account temperature conditions, concrete hardening parameters, geometric characteristics of the formwork, and requirements for minimizing detachment forces.

To achieve the set goal, the following scientific and technical tasks were formulated and solved in the work:

1. Analytical modeling of detachment force.
2. Consideration of temperature conditions and hardening kinetics.
3. Statistical modeling.
4. Comparative analysis of modular and panel formwork.
5. Integration of the methodology into the optimization proces.

THE PURPOSE OF THE WORK

The object is a technological process of forming vertical monolithic structures using group mobile formwork modules.

The subject is the mechanics of detachment of the flexible forming element and the parameters of the roller system ensuring minimal energy load under stable concreting cycles.

The study employs:

- analytical modeling of the tear force through the energy equations of bending and adhesion;
- mechanics of composite tapes to determine the effect of R on the curvature $\kappa = 1/R$;
- early-age concrete strength models (time – temperature maturity);
- statistical modeling (Monte Carlo) with 10^4 scenarios;
- numerical optimization (for different temperatures);
- comparative structural and mechanical analysis of modular and panel formwork;

- technological analysis of the impact of optimal R on the rate and turnover of formwork.

Traditional panel formwork systems (Fig. 1, a) are the most common means of forming vertical monolithic structures in civil and industrial construction. Their design scheme is based on the use of rigid frame or plywood - steel panels, which are installed on the design geometry using spacers, tie elements and fasteners. The formation of the concrete surface occurs under conditions of complete compression of the concrete by the panel over the entire height of the structure. After the concrete hardens, the formwork is dismantled, cleaned and moved by crane or manual means to the next grab.

A characteristic technological feature of panel systems is the vertical tear-off force that occurs along the entire height of the panel (2–3 m). During dismantling, there is a significant bending of the panel and an uneven distribution of adhesive forces, which requires the application of a noticeable force manually or using crane equipment. This can lead to defects in the concrete surface, local delamination or damage to the edges. In addition, the panel system has limited turnover, significant weight, high labor intensity of assembly and disassembly operations and dependence on the rate of hardening of the concrete, which makes it difficult to accelerate the concreting cycle.

In contrast, the belt-type modular formwork proposed in this study (Fig. 1b) is a new technological solution based on the use of a flexible forming element (formwork belt) that moves around supporting rollers. During the module's ascent, the belt detaches tangentially from the concrete surface at the lower part of the formwork, creating a localized detachment zone whose radius is determined by the roller diameter.

Such a scheme fundamentally changes the mechanics of the process:

- the separation zone is small (5–12 cm), unlike 2–3 m in panel formwork;
- the separation occurs smoothly and evenly, with minimal effort;
- the bending of the tape compensates for contact adhesion, reducing energy consumption;
- the quality of the concrete surface is improved due to the absence of sharp tear-off pulses;
- reduces dependence on manual operations and the need for a crane;
- Formwork turnover increases and overall concreting cycles are reduced.

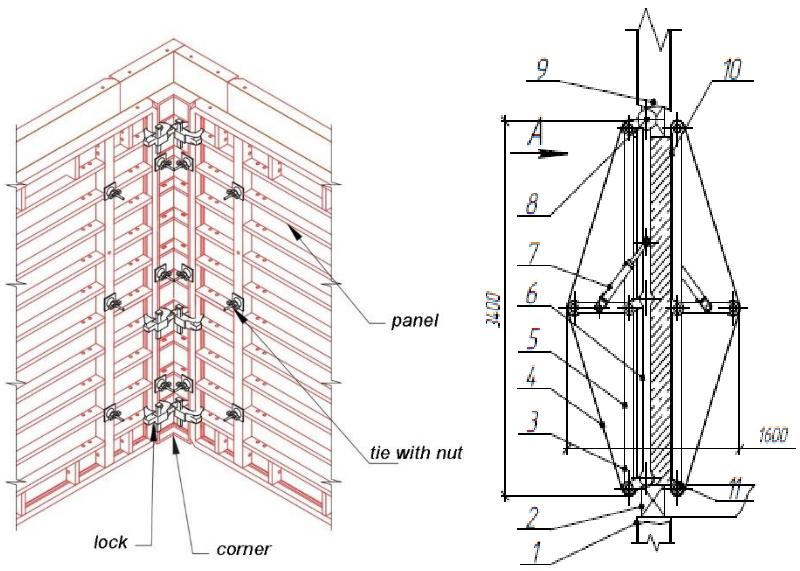
The belt system technologically better meets the requirements of continuous and sequential mechanization, allows for the formation of vertical structures with overlaps and integrates with automated lifting mechanisms. This makes it promising for use in group modular complexes capable of providing high productivity in multi-storey buildings, especially with the modular principle of construction.

The structure of the process of concreting a vertical structure with a belt-type modular formwork is given in Table 1.

Therefore, to determine the parameters of the belt-type modular formwork, we will define the force of separation of the belt-type from the placed concrete as the determining factor [1-6].

In the first stage, we will find the optimal radius R(or diameter$D = 2R$ formwork roller, in which:

- the force required to tear the tape off the concrete surface $F(R, t)$is minimal (or has a sufficient safety margin),
- at the same time, technological requirements are met (allowable lifting time t_{lift}, permissible cycles, module dimensions),
- The dependence of the adhesion of the separation on the degree of hardening of the concrete $f_C(t)$, which depends on the temperature (maturity method), is taken into account.



a *b*

Fig. 1. Technological equipment for monolithic concreting: *a* – panel formwork [7] ; *b* – belt-type modular formwork [8]

Table 1. Structure of the process of concreting a vertical structure with a belt-type modular formwork

Code	Name process	Characteristic	Medium labor intensity , man-hours
O1	Installation of the guide frame	Installation guides elements , check verticality	2.23
O2	Installation modules	Fastening on anchor supports, connection hydraulic systems	1.95
O3	Reinforcement sections	Stacking fittings , inspection position	3.10
O4	Concreting	Mixture feeding , vibration , compaction control	0.58 per 1 m³
O5	Exposure and curing control	Preparing for the climb	0.40
O6	Module lift	Hydraulic drive operation , synchronism control	0.88
O7	Self-cleaning ribbons	Cleaning from sticking , tension check	0.25
O8	Regulation parameters	Adjustment widths pylon , angle of inclination	0.30
O9	Dismantling the system	Disconnection modules , moving to a new one section	1.85

Approach: energy/mechanical — we use the classical division into two component separation forces:

1. the energy of adhesion failure of the concrete-tape bond (adhesive part), which increases with the age of the concrete;
2. the contribution of the bending of the tape around the roller (the bending component), which increases with decreasing R.

The total tear force per unit width $(N/m)$is approximately:

$$p(R,t) = \Phi(\theta) + (G_C(t) + \frac{B}{2R^2}),$$

where $G_C(t)$— the fracture energy per unit width (J/m^2) depends on the age and curing temperature of the concrete; B— the bending stiffness of the tape $(N \cdot m)$; $\Phi(\theta) = \frac{1}{1-\cos\theta}$— the correction factor for the contact angle (takes into account that the separation occurs at a certain angle of rotation. Total force: $F(R,t) = p(R,t) \cdot W$,

where $W$is the width of the belt-type modular formwork (m).

Methodology parameters

Required:

- W— width of the belt / forming surface (m).
- H— formwork height (m) or module height.

- t— time from pouring to the moment of separation / lifting (hours).
- $T(\tau)$ — temperature regime of concrete (°C) as a function of time.
- R_{max}, R_{min}— permissible limits of the roller radius according to the design.
- F_{max} — maximum available tear-off force of the mechanism , N.
- f_{c28} — design grade compressive strength of concrete at 28 days, MPa.

Material /design parameters:

- E_t, $\upsilon_t$is the elastic modulus of the tape material and Poisson's ratio.
- t_t— tape thickness , m.
- θ— contact angle (radians). For “tangential” contact, 30 ^{0} …60 ^{0} .
- Communication parameters k_g, α for the function$G(t)$.

Nominal technological:

- t_{reg}— desired time to rise (maximum) , hours.
- f_{reg}— minimum concrete strength for safe lifting/loading , MPa .

To take into account the temperature effect, we use the maturity method (Nurse – Saul) .

Maturity level:

$M(t) = \sum_{i=1}^{n}(T_i - T_0)\Delta t_i$,

where $T_i$is the average temperature of concrete in the interval Δt_i, °C ; T_0— base temperature , °C.

Let us denote it M_{28} as the measure of maturity at 28 days under standard conditions.

The relationship between strength and maturity, empirical relationship [9-18]:

$$f_c(t) = f_{c28}(\frac{M(t)}{M_{28}})^{\beta},$$

where $\beta$is the exponent (usually (0,4)–(0,8), for ordinary concretes about (0,5).

In the absence of real temperature data, a simple time approximation can be used [9-18] :

$$f_c(t) = f_{c28}\frac{t}{t+a},$$

where $a$is an empirical parameter (hours or days).

The maturity method makes it possible to link the temperature in the hardening mode with the rate of strength gain - this is the basis for determining the moment of safe lifting in various weather conditions.

The fracture energy when the tape is pulled away from the concrete surface G_C(unit: J/m^2) correlates with the tensile/rupture strength of the concrete (e.g., ideal tensile strength f_t).

Let's assume:

$$G_C(t) = k_g \cdot f_t(t) \cdot \delta_c,$$

where

- $f_t(t)$— tensile strength of concrete (MPa) at the moment t(can be calculated from $f_c(t)$the empirical dependence),
- δ_c— characteristic displacement (delamination) upon adhesion failure (m) — experimental parameter of order $10^{-5} - 10^{-3}$m,
- k_g— coefficient that takes into account the surface type, roughness, and external adhesion conditions.

It is practically convenient to use the proportion (empirical) [14] :

$f_t(t) \approx c_t f_c(t)^{\gamma}$,

where $c_t$and $\gamma$are empirical constants (for example, for most concretes $f_t(t) \approx 0{,}1 f_c$) .

The tape has a bending stiffness per unit width [9-18] :

$$B = \frac{E_t t_t^3}{12(1-\vartheta_t^2)},$$

unit: N m (per 1 m width). Here $E_t$is the elastic modulus of the tape, $t_t$is the tape thickness in m, $\vartheta_t$and is the Poisson's ratio of the tape.

The effect of bending on the energy of separation (per unit width) is approximately:

$$E_{band}(R) \approx \frac{B}{2R}.$$

This shows a rapid increase in the energy component as (R) decreases.

If the tape bends at an angle θat the beginning of the tear, then its geometry coefficient is determined by [9-18]:

$$\Phi(\theta) = \frac{1}{1-\cos\theta}.$$

When $\theta \to 0$this factor is large (a certain conservatism), when it $\theta = \pi$is exactly 1/2. In practice, the value$\boldsymbol{\theta}$ is chosen based on the actual contact profile (typically (30 ^{0} –90 ^{0}). If the system is "tangential" (small $\boldsymbol{\theta}$), Φit increases significantly p: the separation becomes more energy-intensive .

Tearing force per unit width:

$$p(R,t) = \Phi(\theta)(G_c(t) + \frac{B}{2R}), N/m.$$

Total tear-off force:

$$F(R,t) = p(R,t)W, N.$$

Assumption: we neglect the friction of the tape on the surface of the pressure plate.

When selecting R, the following two conditions must be satisfied:

1. Concrete strength sufficient for lifting/loading (design limit): $f_c(t_{lift}) \geq f_{reg}$.
2. Mechanical capacity of the mechanism lifting: the breakaway force must not exceed the available capabilities: $F(R,t_{lift}) \leq F_{act.max}$.

Also, a safety margin condition is desirable S:

$$S = \frac{F_{act.max}}{F(R,t_{lift})} \geq S_{req},$$

$S_{req} = 1{,}2 \ldots 1{,}5$.

Let t_{lift}be the estimated lifting time (depends on the organization of work and the ambient temperature [1-4]). We are looking for $R \in [R_{min}, R_{max}]$, which satisfies the constraint and optimizes the criterion. Possible options for the objective function:

Option A — minimizing the pull-off force:

$$\min_{R_{min} \leq R \leq R_{max}} F(R,t_{lift}),$$

under restrictions:

$$f_c(t_{litf}) \geq f_{req}, \quad F(R,t_{lift}) \leq F_{act.max}.$$

Option B — minimizing cycle time under force limitation (adaptation): choose the minimum t_{lift}(i.e., faster rise) provided that there exists Rsuch that $F(R,t_{lift}) \leq F_{act.max}$. Here Rcan be an arbitrary parameter or a given one.

Option C — multi-criteria optimization: minimize the total indicator $\alpha \cdot T_{prod} + \beta \frac{F}{F_{act.max}}$, where T_{prod}— technological time (depends on t_{lift}, and α, β— weighting factors.

In a simple implementation, we note analytically: $F(R,t)$decreases with increasing Rthrough $B/2R^2$— hence from the point of view of the bending component it is better to choose the largest possible R, but design constraints and the influence on $G_c(t)$(due to increased contact) may change the solution.

In panel formwork, the separation is performed normally to the entire area (height 2–3 m), and the separation force acts over the entire contact surface.

We assume that the force is determined by the adhesion energy per area S=W · HS, and the effective "arm" of separation is proportional to H/2:

$$F_{sh}(H,t,T,W) = \alpha G_c(t,T)WH,$$

where α≈1.5–2.0 is the correction factor for the non-ideality of separation (due to uneven adhesion).

The implementation of the methodology was performed in Python for: panel and strip formwork, strip width 1, 1,2, 1,5 1,8; panel and module height up to 1,6 m, 2 m, 3 m; strip material – rubber; panel material – metal; formwork module width 1,2 m, concrete hardening temperature 10, 20, 30^{0}C.

The graphical results presented in the methodology demonstrate the typical nonlinear behavior of the pull-out force F(R) for the strip surface of the formwork (Fig. 2-5).

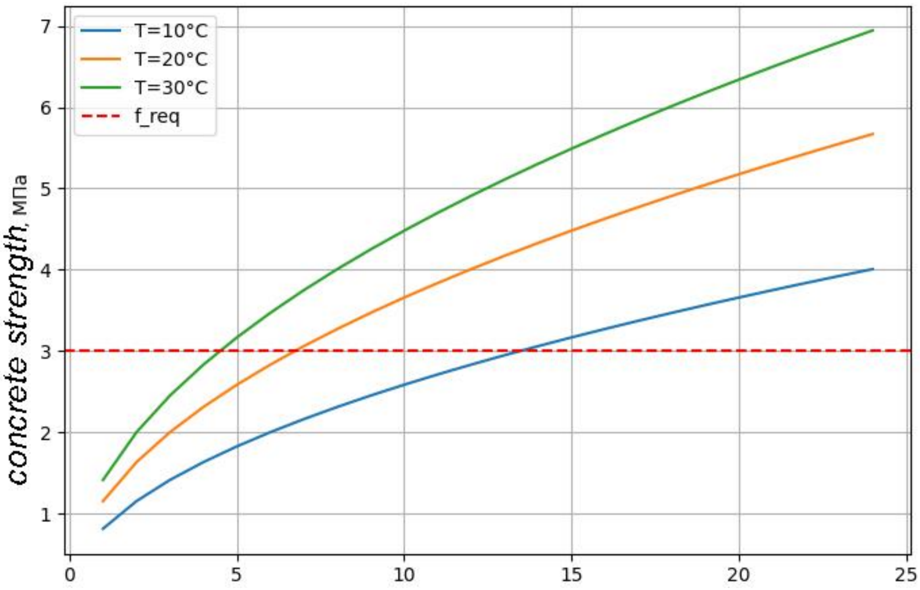


Fig. 2. Graphical representation of the development of concrete strength as different ambient temperatures

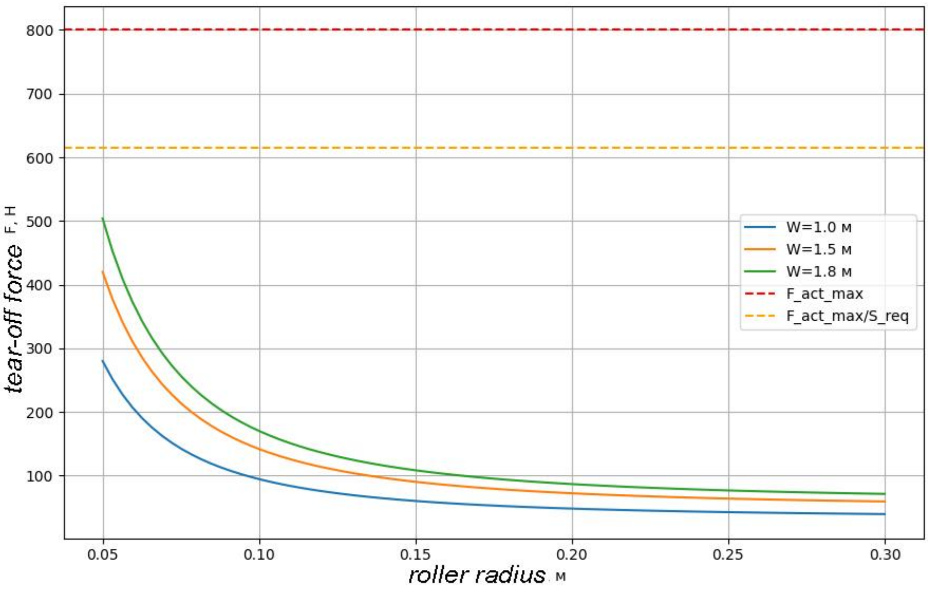


Fig. 3. Graphical representation of the change in the tear-off force of the formwork module tape when changing the concreting width for 20 ^{0} C.

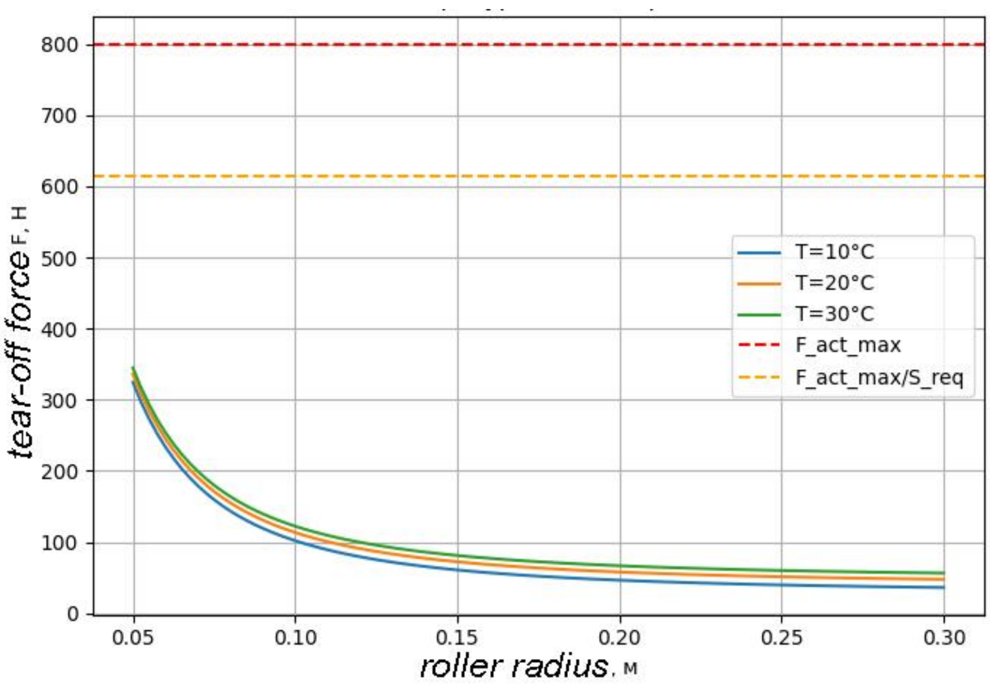


Fig. 4. Graphical representation of the change in the tear-off force of the formwork module of the shield when the ambient temperature changes for a module width of 1.6 m, a displacement time of 8 h.

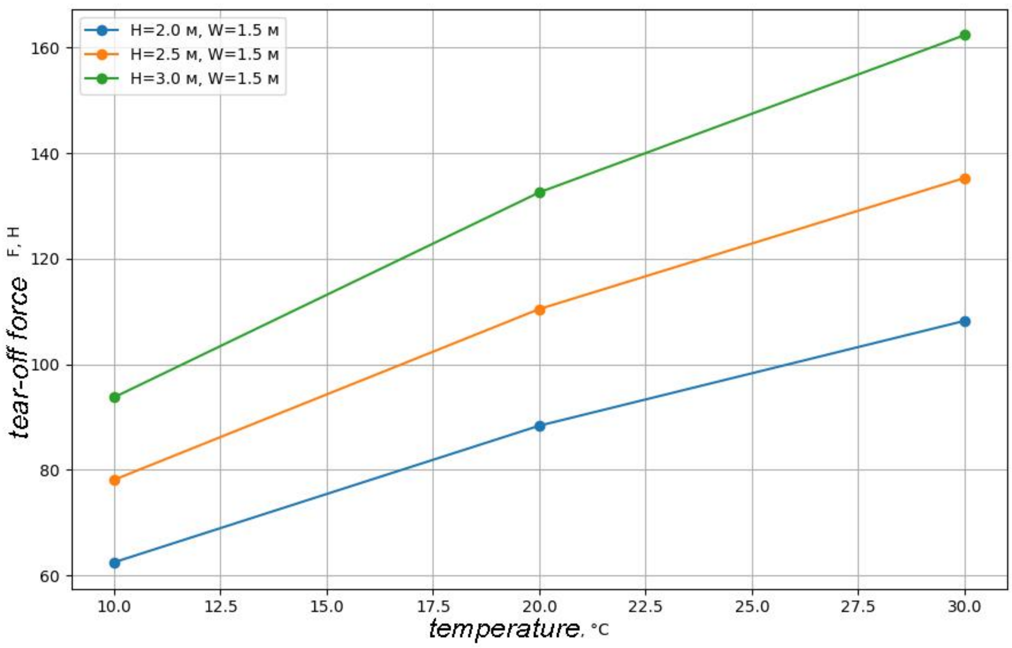


Fig. 5. Graphical representation of the change in the formwork shield separation force when changing the concreting height for 20 ^{0}C

The graphical results presented in the methodology demonstrate the typical nonlinear behavior of the pull-out force F(R) for the strip surface of the formwork.

When the roller radius R decreases, the separation force is:

- increases sharply for R < 200–250 mm,
- moderately decreases with increasing R to 300–400 mm,
- approaches the asymptotic region for R > 450–500 mm.

With a small value of the roller radius, the tape must bend under a much larger curvature, which: increases the bending resistance moment, increases the energy component of the separation, and creates a peak contact stress in the lower zone of the concrete.

The graph of the R_opt (T) dependence shows a monotonic decrease in the optimal R with increasing temperature.

That is, at high temperatures, concrete gains strength faster, respectively, the adhesion component G□(t) increases, and the permissible F_max is not achieved even at lower R.

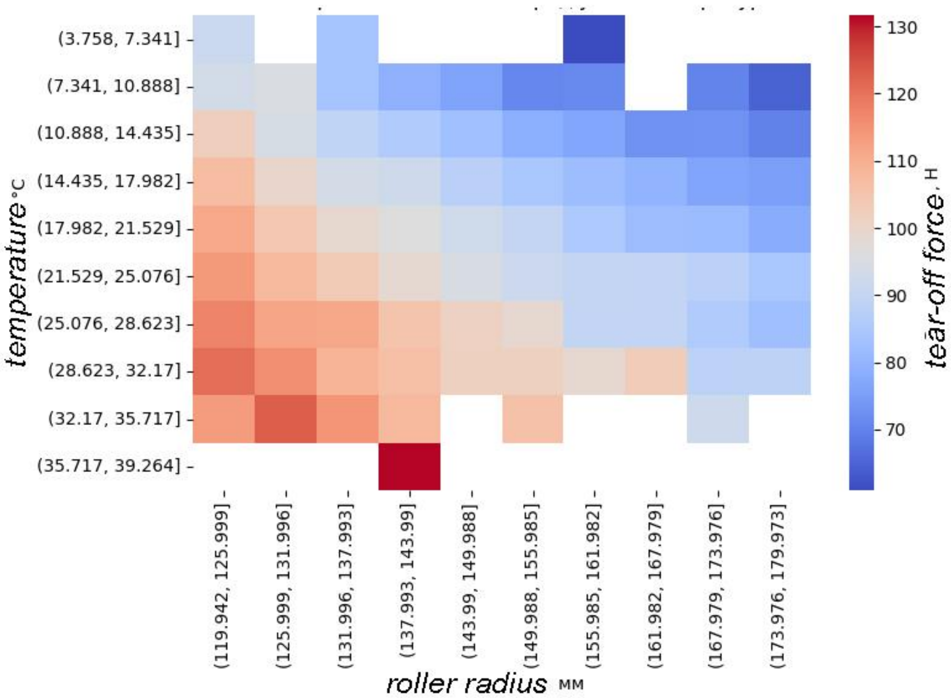


Fig. 6. Monte Carlo simulation of the minimization of the tear-off force

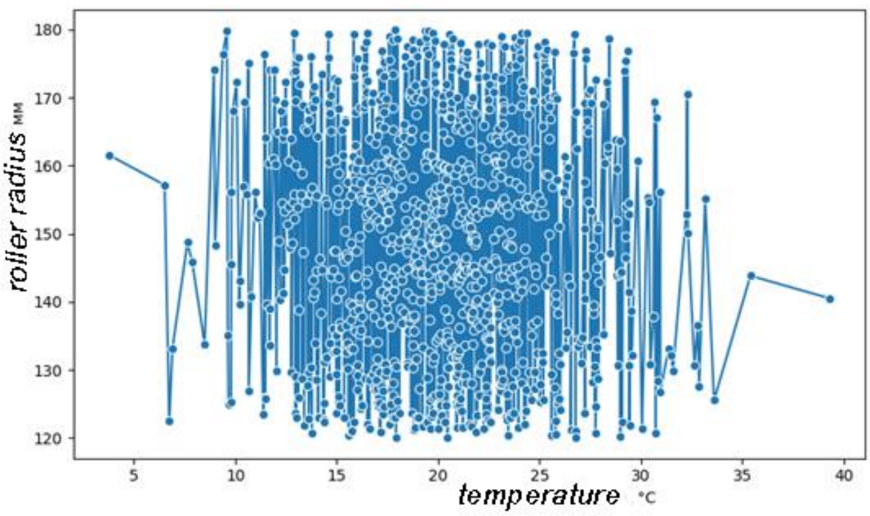


Fig. 7. Monte Carlo simulation of the dependence of the optimal belt roller radius on ambient temperature

Used in the methodology for estimating uncertainties allows us to determine: the randomness of temperature fluctuations ±5…10 °C; variations in concrete strength at an early age; possible deviations of the tape thickness ±10%; errors in measuring the contact angle θ (Fig. 6,7).

In the diagram (Fig. 7), a «cloud» of *F(R)* scenarios can be observed: for small *R* (100–150 mm), there is high dispersion — indicating system instability; for *R* > 300 mm, the curve stabilizes and the spread of scenarios decreases. Such analysis shows the reliability of the solution when changing hardening conditions, allows you to choose a diameter with the maximum technological margin, and allows you to design equipment for the “worst case scenario.” Therefore, the range R = 300–450 mm demonstrates the minimum risk of increasing tear-off forces.

CONCLUSIONS

the obtained analytical data show a radical difference in the mechanics of separation: for modular strip formwork, the separation zone is local, in the lower part, the “shoulder” of the separation force is minimal (depends on the radius of the roller), the value of the force F is 70–150 N. For panel formwork, separation occurs along the entire height of the panel (2–3 m), the “shoulder” of the force is H/2 (tens of times larger), F is 400–700 N, i.e. 3–8 times larger.

Therefore, panel formwork has linearly increasing forces with height, while in a modular system the forces act pointwise and for a short time - therefore the formwork removal process is "soft", does not disturb the concrete surface, allows for early lifting, and is less critical to adhesion heterogeneity.

Graphical dependencies confirm that the optimal roller diameter is not just a design parameter, but a critical element of technological safety and efficiency of mobile modular formwork. This parameter is influenced by a combination of: temperature conditions, concrete hardening dynamics, belt bending mechanics, roller geometry, and lifting mechanism features.

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Методика визначення параметрів стрічкового опалубного модуля для будівельних вертикальних залізобетонних конструкцій

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Анотація. У статті представлено розгорнуту методику визначення, аналізу та оптимізації параметрів стрічкового опалубного модуля, що застосовується для формування вертикальних залізобетонних конструкцій у складі групових механізованих систем. Особливу увагу приділено механіці взаємодії гнучкої формувальної стрічки з бетоном на ранніх стадіях твердіння, де ключовим фактором є дотичне відривне зусилля, яке залежить від діаметра та конфігурації роликової системи, ширини стрічки, висоти модуля, температурного режиму та кінетики набору міцності. Запропонована модель демонструє, що локалізована зона тангенціального відокремлення стрічки забезпечує суттєве зниження енерговитрат, мінімізацію пікових навантажень на бетон і зменшення ймовірності дефектів поверхні, що вигідно вирізняє стрічкову опалубку серед традиційних щитових систем.

Створено математичну модель технологічного потоку комплексу модулів на основі змішаного цілочислового лінійного програмування (MILP), яка дозволяє визначати оптимальні параметри частоти підйому, кількості модулів у роботі, раціональних діаметрів роликів та часових інтервалів бетонування відповідно до виробничих і технологічних обмежень. Варіаційні та статистичні розрахунки, виконані з урахуванням температурних коливань, марок бетону, реологічних змін і стохастичних відхилень процесу, підтвердили можливість стабільного функціонування системи за різних умов. Графічні залежності демонструють потенційне скорочення тривалості бетонування на 18–35 %, зниження відривних зусиль у 2–4 рази та підвищення оборотності формувальних модулів.

Результати дослідження становлять наукове підґрунтя для проєктування механізованих опалубних комплексів нового покоління, що здатні забезпечити підвищену продуктивність, якість формування та адаптивність до зовнішніх умов. Запропонована методика також створює передумови для побудови цифрових двійників технологічних процесів, впровадження систем автоматизованого моніторингу SCADA та інтеграції BIM-рішень у процес керування груповими стрічковими модулями.

Ключові слова: груповий опалубний модуль, стрічкова опалубка; щитова опалубка; дотичний відрив; ролик опалубки; монолітні пілони; технологічний цикл; оптимізація; MILP; BIM; SCADA; технологія монолітного будівництва; твердіння бетону; автоматизація опалубних систем.