MINISTRY OF EDUCATION AND TRAINING	MINISTRY OF CONSTRUCTION

VIETNAM INSTITUTE FOR BUILDING SCIENCE AND TECHNOLOGY

NGUYEN CHI HIEU

EFFECTS OF PRESTRESS LOSSES ON REALIBILITY OF POST-TENSIONED SLAB WITH BONDED TENDONS

BRIEF ENGINEERING DOCTORAL DISSERTATION

SPECIALITY: ENGINEERING CONSTRUCT CIVIL CONSTRUCTION AND INDUSTRY
CODE: 62.58.02.08

Supervisors
1. Associate Professor Dr. Nguyen Xuan Chinh
2. Dr. Le Minh Long

HANOI, 2014

The dissertation is completed at

Vietnam Institute for Building Science and Technology - Ministry of Construction

Supervisors:

1. Associate Professor Dr. Nguyen Xuan Chinh

2. Dr. Le Minh Long

Examiners:

Reviewer 1: Professor Dr. Hoang Xuan Luong

Reviewer 2: Associate Professor Dr. Nguyen Tien Chuong

Reviewer 3: Dr. Hoang Quang Nhu

The dissertation will be defended against IBST's doctoral committee at the meeting room No.2 - Vietnam Institute for Building Science and Technology - Ministry of Construction, 81 Tran Cung - Nghia Tan - Cau Giay - Ha Noi.

Time: …, … July, 2014.

The dissertation can be found at:

1. National Library of Vietnam;
2. Library of Vietnam Institute for Building Science and Technology - Ministry of Construction.

PREFACE

In Vietnam, many high-rise buildings have applied pre-stressed technology. It is shown that cracks appear in some buildings after a period of 5-6 years in use. Others have cracks immediately after prestressing.

Defining causes of crack in prestressed concrete floor can help limit damage of structures not only during design stage, in construction process, or preparation of operational guidelines and maintenance works. Therefore, it is very important to review of structural design and construction to find out causes of prestressed concrete floor crack.

Incorrect calculations of prestress losses in strands in design stage, as well as strand profile installation tolerances, understress or overstress of tendons or use of materials with mechanical and physical properties different from that of the design materials directly effect on causes of floor crack. The errors mentioned above relate to many factors such as friction coefficient between tendons and sleeve, coefficient of tendon profile variation, anchorage draw-in, actual strength and modulus of elasticity of materials, climatic conditions, environmental temperature, basic stress relaxation of tendons, tensioning force, etc…

Hence, there should be study to evaluate effects of prestress losses on cracks of prestressed concrete floor.

Effects of prestress losses occurred during construction and operation of buildings are very complex. For assessing influences of prestress loss types on cracking resistance of floor, reliability theory is one of the effective and advanced methods that can be used to deal with considered problem.

CHAPTER I: OVERVIEW

I.1. SOME STUDIES IN VIETNAM AND INTERNATIONAL RELATED TO RELIABILITY OF PRESTRESSED CONCRETE STRUCTURES

I.1.1. International studies

In this section, the dissertation presents some of the published results of authors on the world researched about prestress losses, assess impact of prestressed concrete corrosive on reliability on structure, assess fire impact on reliability of structure, evaluate reliability of prestressed concrete girders, evaluate reliability of nuclear reactor structures, optimal design associate with reliability problems, reliability of prestressed concrete floor structures, etc...

Fabio Biondini and his colleagues assess reliability of prestressed concrete girders in 2004, focusing on reliability of prestressed concrete cantilever bridge structure. Considered random variables include material characteristics such as concrete strength, intensity, area of steel and prestress strands, geometry dimensions and loads. The research evaluates reliability of structure when considering crack in limit states.

For evaluating reliability of nuclear reactor structures, M.D. Pandey (1997) presents effects of prestress losses in bonded strands to reliability of nuclear reactors. Random variables include compressive strength, tensioning, and elastic modulus of concrete, elastic modulus of prestress strand, weight and pressure in reactors.

For design optimization associated with reliability, AS Al-Harthy and D.M. Frangopolt (1997) study combination between design optimization and reliability of prestressed concrete beam structures. Load parameters, compressive, tensile strength of concrete, prestress levels etc… are considered as random variables.

Some studies also have contributed to assessing reliability of prestressed concrete floor structure. Thamarie Jayasinghe (2011) estimates long term deformation of beams and post - tensioning floor in high-rise buildings in accordance with the AS 3600-2009 standard. Random variables include tensile strength of concrete, time dependent prestress losses, etc...

I.1.2. Studies in Vietnam

This section presents some research outcomes of reliability of civil and traffic constructions, irrigation and marine works, and design optimization associated with the reliability problems.

In the construction sector, authors that can be mentioned are Pham Khac Hung, Nguyen Van Pho, Le Xuan Huynh, Le Ngoc Thach, Nguyen Xuan Chinh who have made contributions through researches and literature about reliability. Nguyen Xuan Chinh (2003) determines probability of failure and reliability index of some construction works. The research introduces a method for assessing the reliability of building by means of β reliability index. Random parameters are concrete strength, which is collected through testing results of mechanical and physical properties of the material. In 2006, Nguyen Van Pho, Nguyen Xuan Chinh and Ta Thanh Van published research on a method of assessing reliability of construction.

In the field of traffic works, irrigation and marine works, Phan Van Khoi, Do Van De, Nguyen Vi and many others have also made some contributions. Do Van De (2007) studies on determination of reliability of wave loads acting on large-size marine constructions, rotating block form, using boundary element method. Nguyen Vi (2009) simulates durability distribution and internal power in load-bearing structures to determine reliability of ports.

Le Xuan Huynh, Do Van De and some others also made contributions in the field of design optimization.

Researches on reliability of prestressed concrete structures are limited.

I.2. TECHNOLOGY DESIGN, CONSTRUCTION OF ƯLT BTCT AND APPLICATION SITUATION IN VIETNAM

This section presents classification, advantages and disadvantages of prestressed concrete structures, as well as application of the structure in Vietnam. Comparisons between bonded and unbonded post - tensioning concrete floor are also given. In addition, design process and construction of prestressed concrete structure is also presented. Based on those reviews, some problems in applying of prestressed concrete structure in Vietnam are finally presented.

I.3. SOME PROBLEMS EXIST IN DESIGN, CONSTRUCTION AND USING OPERATION PRESTRESSED REINFORCED CONCRETE FLOOR IN VIETNAM

I.3.1. In term of design

At present designing of prestressed concrete floor are mainly carried out by using commercial softwares such as SAFE and Adapt floor Pro. The softwares use input parameters given by users to calculate prestress losses. However, long-term prestress losses are omitted in the calculations. Designers often estimate percentage of long-term prestress losses based on tension force in tendons and assign directly to the software. By this way, impact of humidity, environmental temperature around the building, and basic stress relaxation of tendons are not fully considered. The procedure often causes significant errors in estimation of long-term prestress losses and affects to stress in concrete during operation period.

Other input parameters such as material mechanical and physical properties and tensioning forces are usually chosen deterministically by designers without considering random characteristic of the variables. This may lead to errors in prestress losses. In fact, these parameters fluctuate.

Designers rarely seek for an optimal solutions associated to number of strands and slab thickness to ensure the best design in terms of technical issues and cost.

I.3.2. Construction and operation

Process of creating strand profile by support bars may have many technical flaws causing erroneous of tendon maximum deflection in comparison with the design values. The errors not only affect the prestress losses caused by friction but also directly affect stress in concrete due to eccentric torque of tendon.

Tension force is selected as a fixed value. However, it varies on site depending on construction equipment, workers' skill when operating equipment. The problems greatly affect remaining forces in tendons, and stresses in concrete shall difference the original design values.

Inappropriate execution during operation is also considered. Structures are often designed with respected to local environmental factors. However, when the initial functions are changed or changing on conditioning schemes, temperature and humidity may be significant different with design values, leading to change of long-term prestress losses of tendons.

Hence, study effects of prestress losses on reliability of prestressed concrete floor are necessary. In addition, research on reasonable design of prestressed concrete floor to ensure technical factors and economic issues is also considered.

I.4. OBJECTIVES OF THE THESIS

Subject and scope of research: To study some parameters affecting prestress losses in tendons such as coefficient of friction between tendons and sleeve, coefficient taking into account of tendon profiles, anchorage draw-in action, actual strength and elastic modulus of materials, climatic conditions and environmental temperature, basic stress relaxation of tendons, construction process, etc.., which are influence to reliability of bonded post - tensioning concrete floor taking into account crack control criteria in Vietnam practice.

Research Methodology: 1) Based on some international design codes of prestressed concrete structure, study influences of some factors that cause prestress losses. Develop a program to evaluate and assess prestress losses; 2) Assess some random parameters related to prestress losses influence to reliability of bonded post-tensioning concrete floor through data collected from laboratories and construction practice.

Purposes of the research: 1) Assess effects of some types of prestress losses on reliability of bonded post-tensioning concrete floor. 2) Evaluate factors affecting prestress losses and affecting to reliability of bonded post-tensioning concrete floor, with consideration of economic effective problems. 3) Provide recommendations for selecting of effective design associated with reliability analysis.

Issues should be solved: 1) On the basis of design standards available in Vietnam practice, conduct analyses and evaluations in order to determine appropriate standards used for the research. 2) Develop capacity functions incorporate parameters of materials, construction conditions and environment effects for assessing effects of prestress losses on reliability of bonded post-tensioning concrete floor. 3) Study for choosing appropriate statistics methods used for analyzing data collected from practice. 4) Develop a program to evaluate and assess effects of prestress losses on reliability of bonded post-tensioning concrete floor. 5) Propose recommendations and solutions to improve reliability in design and construction of bonded post-tensioning concrete floor in Vietnam practice.

CHAPTER II: STUDY FOR DETERMINING OF DESIGN STANDARD AND CALCULATE CONCRETE STRESSES IN GENRAL PROBLEMS

II.1. CALCULATION OF PRESTRESS LOSSES ACCORDING TO SOME DESIGN STANDARDS, WHICH ARE APPLICABLE IN VIETNAM

II.1.1. AS 3600-2009

II.1.1.1. Prestress losses due to friction along strand

$$\Delta\sigma_{pa}=\sigma_{pj}(1-e^{-\mu\left(\alpha_{tot}+\beta_p L_{pa}\right)});\Delta P_{pa}=P_{pj}(1-e^{-\mu\left(\alpha_{tot}+\beta_p L_{pa}\right)});P_{pa}=P_{pj}e^{-\mu\left(\alpha_{tot}+\beta_p L_{pa}\right)} \tag{II.1.1a,b,c}$$

II.1.1.2. Prestress losses due to anchorage draw-in action

$$\Delta\sigma_{an}=2Ztg\omega/A_p;\Delta P_{an}=2Ztg\omega \tag{II.1.2a,b}$$

II.1.1.3. Prestress losses due to elastic shortening of concrete

$$\Delta\sigma_{cm}=\sigma_{ci}E_p/E_{cj};\Delta p_{cm}=A_p\sigma_{ci}E_p/E_{cj};\Delta P_{cm}=\Delta p_{cm}\left(n_c-1\right)/2n_c \tag{II.1.3a,b,c}$$

II.1.1.4. Prestress losses due to concrete shrinkage

$$\Delta\sigma_{cs}=E_p\varepsilon_{cs}/\left(1+15A_s/A_g\right);\Delta P_{cs}=A_pE_p\varepsilon_{cs}/\left(1+15A_s/A_g\right) \tag{II.1.4a,b}$$

II.1.1.5. Prestress losses due to creep of concrete

$$\Delta\sigma_{cc}=E_p\varepsilon_{cc};\ \Delta P_{cc}=A_pE_p\varepsilon_{cc} \tag{II.1.5a,b}$$

II.1.1.6. Prestress losses due to stress relaxation of tendon

$$\Delta\sigma_{re}=R\left[1-\left(\Delta\sigma_{cs}+\Delta\sigma_{cc}\right)/\sigma_{pj}\right]\sigma_{pj};\Delta P_{re}=R\left[1-\left(\Delta P_{cs}+\Delta P_{cc}\right)/P_{pj}\right]P_{pj} \tag{II.1.6a,b}$$

II.1.2. BS EN 1992-1-1:2004

II.1.2.1. Prestress losses due to friction

$$\Delta P_\mu(x)=P_{max}(1-e^{-\mu(\theta+kx)}) \tag{II.1.7}$$

II.1.2.2. Prestress losses due to anchorage draw-in action

$$\Delta P_A=2px_A \tag{II.1.8}$$

II.1.2.3. Prestress losses due to elastic shortening of concrete

$$\Delta P_{el}=A_pE_p\Sigma\left[\left(j\Delta\sigma_c(t)\right)/\left(E_{cm}(t)\right)\right] \tag{II.1.9}$$

II.1.2.4. Prestress losses due to shrinkage, creep of concrete and stress relaxation of tendons

$$\Delta P_{c+s+r}=A_p\frac{\varepsilon_{cs}E_p+0{,}8\Delta\sigma_{pr}+\left(E_p/E_{cm}\right)\varphi(t,t_0)\sigma_{c'QP}}{1+\left[\left(E_pA_p\right)/\left(E_{cm}A_c\right)\right]\left[1+\left(A_c/I_c\right)z_{cp}^2\right][1+0{,}8\varphi(t,t_0)]} \tag{II.1.10}$$

II.1.3. ACI 318-08

II.1.3.1. Prestress losses due to friction

$$P_{px}=P_{pj}e^{-(Kl_{px}+\mu_p\alpha_{px})}\ \text{ if }\ (Kl_{px}+\mu_p\alpha_{px})>0{,}3 \tag{II.1.11}$$

$$P_{px}=P_{pj}(1+Kl_{px}+\mu_p\alpha_{px})^{-1}\ \text{ if }\ (Kl_{px}+\mu_p\alpha_{px})\le 0{,}3 \tag{II.1.12}$$

II.1.3.2. Prestress losses due to anchorage draw-in action

$$ANC=\Delta f_s=2E_s\Delta_a/L_s \tag{II.1.13}$$

II.1.3.3. Prestress losses due to elastic shortening of concrete

$$ES=\left(K_{es}E_s/E_{ci}\right)f_{cir}\text{, with bond strand} \tag{II.1.14}$$

II.1.3.4. Prestress losses due to shrinkage of concrete

$$SH=8{,}2x10^{-6}K_{sh}E_s\left(1-0{,}06V/S\right)(100-RH) \tag{II.1.15}$$

II.1.3.5. Prestress losses due to creep of concrete

$$CR=K_{cr}\left(E_s/E_c\right)\left(f_{cir}-f_{cds}\right)\text{, with bond strand} \tag{II.1.16}$$

II.1.3.6. Prestress losses due to stress relaxation of tendons

$$RE=[K_{re}-J(SH+CR+ES)]C \tag{II.1.17}$$

II.1.4. TCVN 5574:2012

II.1.4.1. Prestress losses due to friction

$$\Delta\sigma_{ms}=\sigma_{sp}\left[1-\left(1/e^{\omega x+\delta\theta}\right)\right] \tag{II.1.18}$$

II.1.4.2. Prestress losses due to deformation of anchor put in tensioning device

$$\Delta\sigma_{neo} = \left[\left(\Delta l_1 + \Delta l_2\right)/L\right]E_{sp} \qquad \text{(II.1.19)}$$

II.1.4.3. Prestress losses due to shrinkage of concrete $\Delta\sigma_{co}$

II.1.4.4. Prestress losses due to creep of concrete

$$\begin{aligned} &\Delta\sigma_{tb} = \left(150\alpha\sigma_{bp}\right)/R_{bp} \text{ if } \sigma_{bp}/R_{bp} \le 0,75; \\ &\Delta\sigma_{tb} = 300\alpha\left[\left(\sigma_{bp}/R_{bp}\right) - 0,375\right] \text{ if } \sigma_{bp}/R_{bp} > 0,75 \end{aligned} \qquad \text{(II.1.20)}$$

II.1.4.5. Prestress losses due to stress relaxation of reinforcement

$$\Delta\sigma_{ch} = \left[0,22\left(\sigma_{sp}/R_{s,ser}\right) - 0,1\right]\sigma_{sp} \qquad \text{(II.1.21)}$$

II.2. DETERMINATION OF DESIGN STANDARD FOR THE RESEARCH

Based on calculation examples presented in the previous section some comments can be given as follows:

- Calculation procedure according to the AS 3600-2009 is convenient, including the long-term prestress losses estimation.
- The specific climate data of Vietnam is mentioned in the standard.
- In addition, prestress losses due to stress relaxation of tendons take into account for all four factors: air temperature, time effect, basic stress relaxation and ratio between initial stress and ultimate stress of strands.

Thus, AS 3600-2009 is chosen for the research.

II.3. DESIGN PROCEDURE OF PRESTRESSED CONCRETE FLOOR ARCCORDING TO AS 3600-2009

This section presents design procedure according to AS 3600-2009, in which floor crack control is provided.

a) Compressive stress in floor σ_n must not exceed $0,5f_{cp}$: $\sigma_n \le 0,5f_{cp}$ (f_{cp} is compressive strength of concrete at the time of prestressing);

b) Bending tensile stress in floor σ_k under standard loads shall not exceed $0,6\sqrt{f_c^{'}}$ and $\sigma_k \le 0,6\sqrt{f_c^{'}}$. The distance of bonded strands not greater than 300mm and $2,0D_s$.

II.4. DESIGN EXAMPLE OF BONDED POST-TENSIONING CONCRETE FLOOR AND CRACK CONTROL ACCORDING TO AS 3600-2009

This section presents an example of design of bonded post-tensioning concrete floor with crack control criteria. Based on that, formula of calculating stresses in concrete is proposed. Factors effect stresses in concrete and prestress losses are also mentioned.

II.4.1. Stress in concrete

a) Immediately after prestressing: $\overline{\sigma^{*(TT),(TD)}} = -NP^*/bD_s \pm 3NP^*h/\left(bD_s^2\right) \pm 6M^q/\left(bD_s^2\right)$

b) Service period: $\overline{\sigma^{(TT),(TD)}} = -NP\left(bD_s\right) \pm 3NPh/\left(bD_s^2\right) \pm 6M^g/\left(bD_s^2\right)$

Stress in concrete, beside parameters N and D_s, depends on the net force in tendons P^* and force P immediately after prestressing and service period.

II.4.2. Factors effecting P^*

E_p, A_p: Elastic modulus and cross section area of tendon; δ_L: anchorage draw-in level; P_{pj}: prestressing force;

h: sag of tendon; μ, β_p: coefficient of friction, random angle deviation of tendon.

II.4.3. Factors affecting P

E_p, A_p: elastic modulus and cross section area of tendon; k_4, k_6: parameters depend on humidity, environmental temperature;

P_{pj}: prestressing force; R_b: basic stress relaxation of tendon.

II.5. CALCULATION OF STRESS IN CONCRETE FOR GENERAL DESIGN SITUATION OF n SPAN PRESTRESSED CONCRETE SLAB ARCCORDING TO AS 3600-2009

II.5.1. Stress in concrete immediately after prestressing

$\overline{\sigma^{*(TT)}} = \sigma^{*} + \sigma^{*(TT)} + \sigma^{q(TT)}$ - top fiber of section

$\overline{\sigma^{*(TD)}} = \sigma^{*} + \sigma^{*(TD)} + \sigma^{q(TD)}$ - bottom fiber of section

In which, compressive stress in concrete is caused by:

- Tendon prestressing force: $\sigma^{*} = -NP^{*}/\left(bD_{s}\right)$;
- Tendon eccentric moment: $\sigma^{*(TT,TD)} = \pm\left(3NP^{*}h\right)/\left(bD_{s}^{2}\right)$;
- Self-weight load: $\sigma^{q(TT,TD)} = \pm\left(6M^{q}\right)/\left(bD_{s}^{2}\right)$.

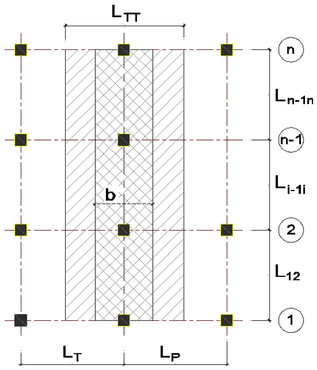


Figure II.5-1: Plan layout of n span floor

Table II.5-3: Stress in concrete immediately after prestressing

Support at axis 1 $\overline{\sigma_{1}^{*(TT)}},\overline{\sigma_{1}^{*(TD)}} =$ $= -\frac{NP_{1}^{*}}{bD_{s}} \mp \frac{3NP_{1}^{*}h}{bD_{s}^{2}} \pm$ $\pm 6qb0,45L_{o,12}^{2}/8bD_{s}^{2}$	Span axes 1,2 $\overline{\sigma_{12}^{*(TT)}},\overline{\sigma_{12}^{*(TD)}} =$ $= -\frac{NP_{12}^{*}}{bD_{s}} \pm \frac{3NP_{12}^{*}h}{bD_{s}^{2}} \mp$ $\mp 6qb0,6L_{o,12}^{2}/8bD_{s}^{2}$	Left side support at axis 2 $\overline{\sigma_{2}^{*(TT)}}(T),\overline{\sigma_{2}^{*(TD)}}(T) =$ $= -\frac{NP_{2}^{*}}{bD_{s}} \mp \frac{3NP_{2}^{*}h}{bD_{s}^{2}} \pm$ $\pm 6qb1,05L_{o,12}^{2}/8bD_{s}^{2}$	Right side support at axis 2 $\overline{\sigma_{2}^{*(TT)}}(P),\overline{\sigma_{2}^{*(TD)}}(P) =$ $= -\frac{NP_{2}^{*}}{bD_{s}} \mp \frac{3NP_{2}^{*}h}{bD_{s}^{2}} \pm$ $\pm 6qb0,975L_{o,23}^{2}/8bD_{s}^{2}$
Left side support at axis i $\overline{\sigma_{i}^{*(TT)}}(T),\overline{\sigma_{i}^{*(TD)}}(T) =$ $= -\frac{NP_{i}^{*}}{bD_{s}} \mp \frac{3NP_{i}^{*}h}{bD_{s}^{2}} \pm$ $\pm 6\frac{0,975qbL_{o,i-1i}^{2}}{8bD_{s}^{2}}$	Right side support at axis i $\overline{\sigma_{i}^{*(TT)}}(P),\overline{\sigma_{i}^{*(TD)}}(P) =$ $= -\frac{NP_{i}^{*}}{bD_{s}} \mp \frac{3NP_{i}^{*}h}{bD_{s}^{2}} \pm$ $\pm 6\frac{0,975qbL_{o,ii+1}^{2}}{8bD_{s}^{2}}$	Span axes i-1,i $\overline{\sigma_{i-1i}^{*(TT)}},\overline{\sigma_{i-1i}^{*(TD)}} =$ $= -\frac{NP_{i-1i}^{*}}{bD_{s}} \pm \frac{3NP_{i-1i}^{*}h}{bD_{s}^{2}} \mp$ $\mp 6\frac{0,42qbL_{o,i-1i}^{2}}{8bD_{s}^{2}}$	
Left side support at axis n-1 $\overline{\sigma_{n-1}^{*(TT)}}(T),\overline{\sigma_{n-1}^{*(TD)}}(T) =$ $= -\frac{NP_{n-1}^{*}}{bD_{s}} \mp \frac{3NP_{n-1}^{*}h}{bD_{s}^{2}} \pm$ $\pm 6\frac{0,975qbL_{o,n-2n-1}^{2}}{8bD_{s}^{2}}$	Right side support at axis n-1 $\overline{\sigma_{n-1}^{*(TT)}}(P),\overline{\sigma_{n-1}^{*(TD)}}(P) =$ $= -\frac{NP_{n-1}^{*}}{bD_{s}} \mp \frac{3NP_{n-1}^{*}h}{bD_{s}^{2}} \pm$ $\pm 6\frac{1,05qbL_{o,n-1n}^{2}}{8bD_{s}^{2}}$	Span axes n-1,n $\overline{\sigma_{n-1n}^{*(TT)}},\overline{\sigma_{n-1n}^{*(TD)}} =$ $= -\frac{NP_{n-1n}^{*}}{bD_{s}} \pm \frac{3NP_{n-1n}^{*}h}{bD_{s}^{2}} \mp$ $\mp 6\frac{0,6qbL_{o,n-1n}^{2}}{8bD_{s}^{2}}$	Support at axis n $\overline{\sigma_{n}^{*(TT)}},\overline{\sigma_{n}^{*(TD)}} =$ $= -\frac{NP_{n}^{*}}{bD_{s}} \mp \frac{3NP_{n}^{*}h}{bD_{s}^{2}} \pm$ $\pm 6\frac{0,45qbL_{o,n-1n}^{2}}{bD_{s}^{2}}$

In Table II.5-3, top fiber stress takes “+” in the sign $\pm$; bottom fiber stress takes “+” in the sign $\mp$.

II.5.2. Stress in concrete in service stage

$\overline{\sigma^{(TT)}} = \sigma + \sigma^{(TT)} + \sigma^{g(TT)}$, (top fiber of concrete section)

$\overline{\sigma^{(TD)}} = \sigma + \sigma^{(TD)} + \sigma^{g(TD)}$, (bottom fiber of concrete section)

In which: q is self-weight and q is total load exerted on floor.

II.6. ACHIEVED RESULTS

Theories of prestress loss calculation according to prevalent standards in Vietnam, including AS 3600-2009, BS EN 1992-1-1:2004, ACI 318-08 and ISO 5574:2012 are presented. The standard AS 3600-2009 is recommended for the parametric studies shown in next part of the thesis.

Design procedure on the basic of moment distribution method, as well as process of checking prestressed concrete floor according to AS 3600-2009 is in introduced. The results shown that condition of allowable stress controlling cracks should be satisfied before proceeding to next steps. The condition should be considered at the beginning steps of determining tendon numbers and slab thickness.

The thesis is limited to examine effects of prestress losses on reliability of bonded post-prestressing concrete floor with respect to the crack control criteria.

Through design examples of bonded post-prestressing concrete floors and checking of crack control by allowable stress method according to AS 3600-2009, factors affecting prestress losses in concrete are clearly shown. Parameters considered in the research are as follows:

- E_p, A_p: elastic modulus and cross section of tendon; h: deflection of tendon;
- δ_L: anchorage draw-in length; P_{pj}: prestressing force;
- k_4, k_6: parameters depend on humidity and environmental temperature;

The calculation of stress in the concrete for general design problem of bonded post-prestressing concrete floor is also presented.

CHAPTER III: DEVELOPMENT OF CAPACITY FUNCTION WITH RESPECT TO CRACK CONTROL CRITERIA AND IDENTIFICATION OF RANDOM VARIABLES THROUGH EXPERIMENTAL DATA

III.1. DEVELOPMENT OF CAPACITY FUNCTION FOR A 3-SPAN FLOOR DESIGNING ACCORDING TO AS 3600-2009

III.1.1. Capacity function with respect to crack control criteria

To control crack of prestressed concrete floor according to the standard, stress in concrete should not exceed allowable values. Capacity function with respect to crack control criteria can be written as follows:

$$M = [\sigma] - \sigma \tag{III.1.1}$$

where: load effects can be determined as stress in concrete σ; bearing capacity is defined as allowable stress $[\sigma]$.

Based on general capacity function with respect to crack control criteria, capacity function can be developed for each of design stages of prestressed concrete floor.

III.1.1.1. Capacity function for stage of immediately after prestressing

$$M = [\sigma]_n - \mathrm{ABS}[\min(\sigma)] \qquad \Rightarrow M = 0{,}5f_{cp} - \mathrm{ABS}\left[\min\left(\overline{\sigma^{*(TT)}}, \overline{\sigma^{*(TD)}}\right)\right] \tag{III.1.2}$$

$$M = [\sigma]_k - \max(\sigma) \qquad \Rightarrow M = 0{,}6\sqrt{f_{cp}} - \max\left(\overline{\sigma^{*(TT)}}, \overline{\sigma^{*(TD)}}\right) \tag{III.1.3}$$

III.1.1.2. Capacity function for service stage

$$M = [\sigma]_n - \mathrm{ABS}[\min(\sigma)] \qquad \Rightarrow M = 0{,}5f_c^{'} - \mathrm{ABS}\left[\min\left(\overline{\sigma^{(TT)}}, \overline{\sigma^{(TD)}}\right)\right] \tag{III.1.4}$$

$$M = [\sigma]_k - \max(\sigma) \qquad \Rightarrow M = 0{,}6\sqrt{f_c^{'}} - \max\left(\overline{\sigma^{(TT)}}, \overline{\sigma^{(TD)}}\right) \tag{III.1.5}$$

Load effects immediately after tensioning ($\overline{\sigma^{*(TT)}}$, $\overline{\sigma^{*(TD)}}$) and service stage ($\overline{\sigma^{(TT)}}$, $\overline{\sigma^{(TD)}}$) are presented in Section II.5. For a 3-span prestressed concrete floor, the problem is presented in section III.1.2 below.

III.1.2. Stress in concrete immediately after tensioning

In Table III.1-2, top fiber stress takes "+" in the sign $\pm$; bottom fiber stress takes "+" in the sign $\mp$.

Table III.1-2: Stress in concrete immediately after tensioning

Support at axis 1 $\overline{\sigma_1^{*(TT)}},\overline{\sigma_1^{*(TD)}}=-NP_1^*/bD_s\mp$ $\mp\frac{3NP_1^*h}{bD_s^2}\pm6\frac{0,45qbL_{o,12}^2}{8bD_s^2}$	Span axes 1,2 $\overline{\sigma_{12}^{*(TT)}},\overline{\sigma_{12}^{*(TD)}}=-NP_{12}^*/bD_s\pm$ $\pm\frac{3NP_{12}^*h}{bD_s^2}\mp6\frac{0,6qbL_{o,12}^2}{8bD_s^2}$	Left side support at axis 2 $\overline{\sigma_2^{*(TT)}(T)},\overline{\sigma_2^{*(TD)}(T)}=-NP_2^*/bD_s\mp$ $\mp\frac{3NP_2^*h}{bD_s^2}\pm6\frac{1,05qbL_{o,12}^2}{8bD_s^2}$
Right side support at axis 2 $\overline{\sigma_2^{*(TT)}(P)},\overline{\sigma_2^{*(TD)}(P)}=-\frac{NP_2^*}{bD_s}\mp$ $\mp\frac{3NP_2^*h}{bD_s^2}\pm6\frac{0,975qbL_{o,23}^2}{8bD_s^2}$	Span axes 2,3 $\overline{\sigma_{23}^{*(TT)}},\overline{\sigma_{23}^{*(TD)}}=-\frac{NP_{23}^*}{bD_s}\pm$ $\pm\frac{3NP_{23}^*h}{bD_s^2}\mp6\frac{0,42qbL_{o,23}^2}{8bD_s^2}$	Left side support at axis 3 $\overline{\sigma_3^{*(TT)}(T)},\overline{\sigma_3^{*(TD)}(T)}=-\frac{NP_3^*}{bD_s}\mp$ $\mp\frac{3NP_3^*h}{bD_s^2}\pm6\frac{0,975qbL_{o,23}^2}{8bD_s^2}$
Right side support at axis 3 $\overline{\sigma_3^{*(TT)}(P)},\overline{\sigma_3^{*(TD)}(P)}=-NP_3^*/bD_s\mp$ $\mp\frac{3NP_3^*h}{bD_s^2}\pm6\frac{1,05qbL_{o,34}^2}{8bD_s^2}$	Span axes 3,4 $\overline{\sigma_{34}^{*(TT)}},\overline{\sigma_{34}^{*(TD)}}=-NP_{34}^*/bD_s\pm$ $\pm\frac{3NP_{34}^*h}{bD_s^2}\mp6\frac{0,6qbL_{o,34}^2}{8bD_s^2}$	Support at axis 4 $\overline{\sigma_4^{*(TT)}},\overline{\sigma_4^{*(TD)}}=-NP_4^*/bD_s\mp$ $\mp\frac{3NP_4^*h}{bD_s^2}\pm6\frac{0,45qbL_{o,34}^2}{bD_s^2}$

III.1.3. Stress in concrete in service stage

The calculations are similar for the stage of immediately after prestressing. Details are presented in the thesis.

III.1.4. Collecting practice statistics data and establishing specific parameters of construction

a) Collect parameters E_p, A_p: from experimental results; b) Collect parameter δ_L: from data measured on sites; c) Collect parameters related to tendon prestressing forces P_{pj} (denoted as P_{pj}^{TT}): prestressing forces P_{pj}^{TT} are examined through collection of construction factor $\varepsilon_L=\Delta L_{TT}/\Delta L_{LT}$, with ΔL_{LT} is theoretical elongation of each strand; ΔL_{TT} is corresponding actual elongation obtained on sites; d) Collect data of environmental temperature (refer to Vietnam Building Codes); e) Collect data of basic stress relaxation R_b, deflection of tendon h: these parameters are considered as variable parameters within given ranges.

III.2. SOME COMMON RANDOM VARIABLES AND CREATING PSEUDO - RANDOM VARIABLES

III.2.1. Some common continuous random variables

This section presents some common continuous random variables. Random variables with normal distribution characterized by expectation μ and variance σ^2 are very commonly used. The probability density function and probability distribution function as follows:

$$f_X(x)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right);F_X(x)=\frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{x}\exp\left(-\frac{(u-\mu)^2}{2\sigma^2}\right)du \qquad \text{(III.2.1)}$$

III.2.2. Creating pseudo-random variables

Main purpose of creating pseudo-random variable is to create a string $\{X_1,\ldots,X_n\}$ of a random variable X, with a given distribution law $F_X(x)$. Creating of pseudo-random variable with an arbitrarily distribution function is implemented through creating a pseudo-random variable with distribution Uniform $U[0,1]$.

III.3. IDENTIFYING A RANDOM VARIABLE

Identifying a random variable is in fact to determine probability density function of the random variable. This section presents two methods of random variable identification, which are histogram method and kernel density function estimation method.

III.3.1. Histogram method

Histogram method utilize empirical graphs of probability density function based on estimating appearing frequency of X_i value of random variable in each domain $[a_k, a_{k+1})$ of discrete value domain $\{a_1, \ldots, a_m\}$.

III.3.2. Kernel density function estimation method

Kernel method (Kernel density estimation) estimates non-parametric probability density function of a random variable based on denominator of the variable. Suppose there is a denominator $\{X_1, \ldots, X_n\}$ of a random variable X, empirical estimation of probability density function is written as follows:

$$\hat{f}(x,h) = \frac{1}{n}\sum_{i=1}^{n} K_h(x - X_i) \tag{III.3.6}$$

Where K is kernel function, h is the *width* of the function. Thus, the key point of this method is to select of kernel function K_h and width h. Some common kernel functions with their width are given in Table III.3-2 and Table III.3 -3.

Table III.3-2: Some common kernel functions

Name of function	Expression
Cosine	$K(z) = 1 + \cos(2\pi z) \quad \text{Khi} \quad \lvert z \rvert < 0,5$
Gaussian	$K(z) = \left(1/\sqrt{2\pi}\right)\exp\left(-z^2/2\right)$
Rectangular	$K(z) = 0.5 \quad \text{Khi} \quad \lvert z \rvert < 1$

Table III.3-3: Width of common kernel functions

Name	Expression
Normal	$h^N = \left[\left(8\sqrt{\pi}R(K)\right)/\left(3\mu_2(K)^2 n\right)\right]^{\frac{1}{5}}\hat{\sigma}$
Silverman	$h^{Silver} = 1.159\left[\left(R(K)\right)/\left(\mu_2(K)^2 n\right)\right]^{\frac{1}{5}}\hat{\sigma}$

Within scope of the dissertation, Gaussian kernel function with Silverman width is chosen. Silverman width correspond to a Gaussian function is shown as follows: $h_{\Phi}^{Silver} = 0.9\hat{\sigma}/\sqrt[5]{n}$ (III.3.7)

III.3.3. Approximation of experimental probability density function

When a probability density function has been estimated, based on its experimental graph, probability distribution model is chosen and experimental values should be fitted. Approximation method commonly used, which is presented in the thesis, is *least squares fitting* method.

III.4. RELIABILITY AND RELIABILITY DETERMINING METHOD

III.4.1. Some basic concepts

This section presents concept of reliability of structures according to EN 1990 - Eurocode - Basic of structural design, International Standard ISO 2394. The standard "Reliability of building structures and foundations - The principles and basic requirements" adopted by the Council of Science of Ministry of Construction defines "*reliability of construction is ability to fulfill its required functions during design service life".*

III.4.2. Stochastic model

Reliability of a system is measured by safety probability of the system.

$$P_s = \text{Prob}[\mathbf{Y} \in W] = \int_{\Omega} I_{\mathbf{Y}\in W}(\mathbf{Y}) f_{\mathbf{Y}}(y)dy \qquad \text{(III.4.2)}$$

where $f_{\mathbf{Y}}(y)$ is probability density function of random vector $\mathbf{Y}$; $\mathbf{I}_{\mathbf{Y}\in W}(\mathbf{Y})$ is indicator function defined as follows:

$$\mathbf{I}_{\mathbf{Y}\in W}(\mathbf{Y}) = 1,\ \text{when } \mathbf{Y} \in W;\ \mathbf{I}_{\mathbf{Y}\in W}(\mathbf{Y}) = 0,\ \text{when } \mathbf{Y} \notin W \qquad \text{(III.4.3)}$$

Stochastic model of reliability problem consists of three steps shown in Figure III.4-1.

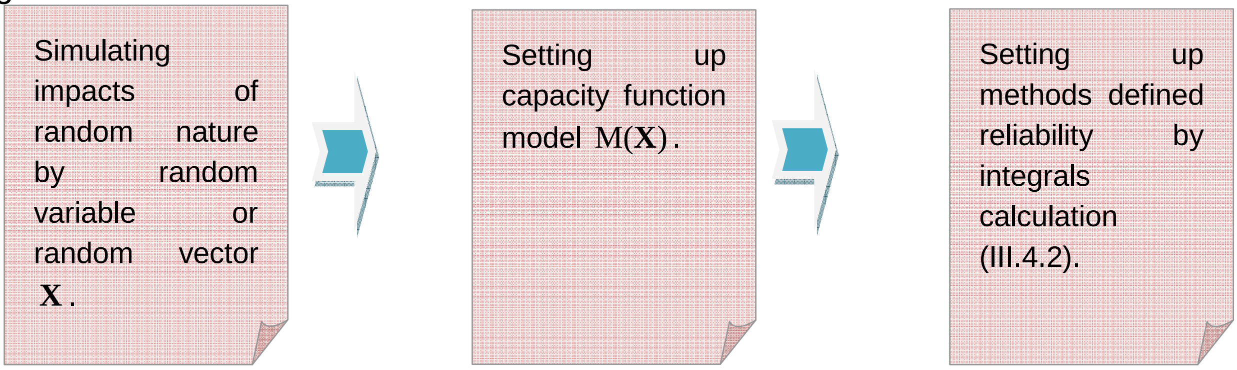


Figure III.4-1: Random Model of reliability problem

One of the objectives of the research is to assess effects of prestress losses on reliability of bonded post-tensioning concrete floor, the random model shown in Figure III.4-1 can be expressed as follows:

- 1st step: refer to section III.2 and III.3.
- 2nd step: refer to section III.1.
- 3rd step: refer to section III.4.3 to III.4.5 below.

III.4.3. Method of reliability index β

Examining a problem of structural design with capacity function in linear form:

$$M = g(R,S) = R - S \qquad \text{(III.4.5)}$$

Safety condition of the structure: $M = g(R,S) > 0$.

Suppose S and R are two random variables that have independent normal distribution probability with expected value and standard deviation, μ_S, σ_S and μ_R, σ_R, respectively. Thus, $M = R - S$ is also a random variable that has a normal distribution with expectation and standard deviation:

$$\mu_M = \mu_R - \mu_S;\quad \sigma_M = \sqrt{\sigma_R^2 + \sigma_S^2} \qquad \text{(III.4.6)}$$

Unsafety probability of structure corresponding to condition $M < 0$ is:

$$P_f = \Phi\left(-(\mu_R - \mu_S)/\sqrt{\sigma_R^2 + \sigma_S^2}\right) = \Phi(-\beta) \qquad \text{(III.4.7)}$$

III.4.4. Hasofer-Lind method

The dissertation presents Hasofer-Lind method. It is shown that this method overcomes limitation of the β method that is depends on type of capacity function and requirement of normal distribution of random variables. Standardization is difficult and capacity function is required to be linear or differentiable.

III.4.5. Monte Carlo Method

Monte Carlo is actually a method that uses pseudo-random numbers to simulate a random problem on the basis of large number rule. Rewriting expression III.4.2 in particular problem with input random vector $\mathbf{X} = [X_1, X_2, ..., X_n]$ and safety domain W defined by condition $M(X_i) > 0$, which leads to expression below:

$$P_s = \int_W \mathbf{I}_{M(\mathbf{X})>0} f_{\mathbf{X}}(\mathbf{x})d\mathbf{x} = \mathbf{E}\left[\mathbf{I}_{M(\mathbf{X})>0}\right] \qquad \text{(III.4.14)}$$

where: $\mathbf{I}_{M(\mathbf{X})>0}=1$ when $M(\mathbf{X})>0$; $\mathbf{I}_{M(\mathbf{X})>0}=0$ when $M(\mathbf{X})\le 0$ (III.4.15)

If there are N implementations of random vector $\mathbf{X}$, it is possible to calculate a denominator consisting of N values of the function $\mathbf{I}_{M(\mathbf{X})>0}$. Then, $\mathbf{E}\left[\mathbf{I}_{M(\mathbf{X})>0}\right]$ can be approximately calculated by averaging denominator.

$$\tilde{P}_s=\mathbf{E}\left[\mathbf{I}_{M(\mathbf{X})>0}\right]=\frac{1}{N}\sum_{i=1}^{N}\mathbf{I}^{i}_{M(\mathbf{X}_i)>0} \qquad \text{(III.4.16)}$$

With this method, input random variables are not necessarily to be normally distributed. The method can be applied even if capacity function is not a mathematical analysis expression nor linear. Figure III.4-5 shows schematic algorithm of Monte Carlo simulation method. Getting results is essentially counting times of fall into the safe domain in total number of simulations N. In fact, it is difficult to determine number of times N to ensure reliability of result. Convergence condition of the estimated value $\tilde{P}_s$ is normally used.

$$\max\left(\tilde{P}_s^{N}-\left[\tilde{P}_s^{N-1},\tilde{P}_s^{N-2},....,\tilde{P}_s^{N-k}\right]\right)\le\varepsilon \qquad \text{(III.4.19)}$$

From the expressions (III.4.19), it can be seen that loop simulation is stop only when largest error of the final estimated value, compared with previous value k, is less than a given value ε.

III.4.6. Calculation examples verifying reliability of the developed program based on Monte Carlo method

This section presents two examples of calculating reliability based on three presented methods to verifying reliability of the program according to Monte Carlo method. The results show that the program based on Monte Carlo simulation method is reliable and can be used when the capacity function is not a mathematically analysis nor linear.

Monte Carlo simulation method is used in the research to determine reliability of post-tensioning concrete floor with respect to crack control criteria satisfying allowable stress.

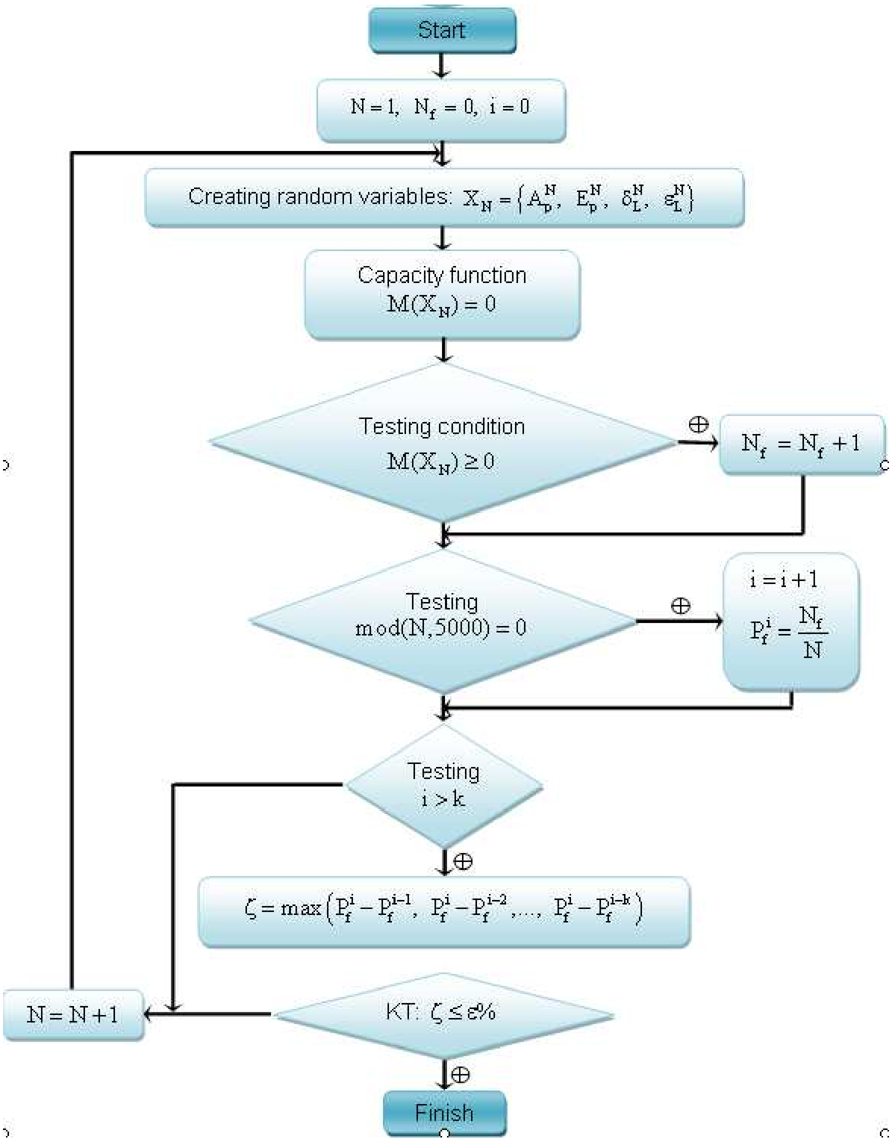


Figure III.4-5: Algorithm diagram of Monte Carlo simulation method

III.5. RANDOM VARIABLES IDENTIFICATION BASED ON EXPERIMENTAL DATA COLLECTED IN VIETNAM

III.5.1. Source of data

Variable parameters including cross section A_p and elastic modulus of tendon E_p , anchorage draw-in level of tendon δ_L and construction effect factors characterized by quantities ε_L are collected from some reliable laboratories as well as projects under construction. These parameters are identified and simulated as random variables. Random variable identification program is written in the Python programming language.

III.5.2. Identification of random variable of tendon cross section A_p

Statistics data of tendon cross sections are shown in Table III.5-3.

Table III.5-3: Statistic data of tendon cross section

12.7mm-diameter tendons											
Unit: mm^2											
101.1	100.4	99.2	99.5	100.5	100.5	99.6	100.7	101.1	99.0	98.6	99.6
99.6	100.4	100.1	99.0	99.9	99.3	101.0	100.8	99.6	100.0	100.4	100.5
100.2	99.3	98.6	98.0	99.0	101.2	98.9	99.0	100.1	100.0	99.5	100.5
100.1	99.7	99.4	99.6	99.4	98.6	99.3	99.8	98.2	100.5	100.0	100.3
99.9	100.5	98.9	99.0	99.5	100.0	99.8	99.9	100.8	99.4	99.7	99.6
99.5	98.5	100.7	99.9	99.1	100.6	99.1	101.4	98.9	99.0	99.9	101.4
98.2	99.7	98.5	99.4	100.3	97.8	98.1	99.8	99.2	97.6	99.9	100.0
100.8	100.2	98.5	99.7	100.3	99.4	99.6	99.7	99.4	99.5	100.0	99.9
100.2	99.6	99.9	99.4	99.9	99.0	99.6	99.0	98.2	99.7	100.5	100.6
99.4	98.5	101.1	99.8	99.0	99.7	99.7	99.4	99.4	99.2	99.0	100.6

With collected data, histogram and kernel smoothing methods are used to calculate probability density function and experiment probability distribution function of cross section random variable. Figure III.5-1 shows probability density functions and experiment probability distribution functions derived from the calculations. Expected value and experimental standard deviation calculated directly from denominator is $\mu = 0,9967\text{cm}^2$, $\sqrt{\upsilon} = 0,0078\text{cm}^2$.

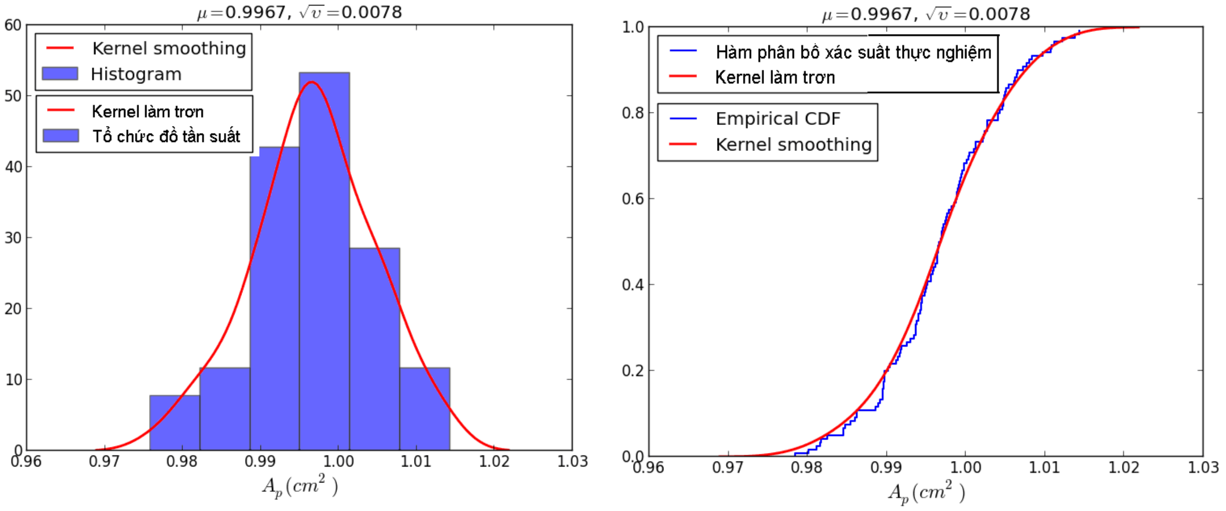


Figure III.5-1: Probability density function (left) and experimental probability distribution function (right) of cross section random variable

It is found that experimental probability density functions based on two methods are quite consistent and have form of normal distribution. It is believed that use of the kernel smoothing method is appropriate in this case. Similar condition can also be seen in the probability distribution function.

On the basis of normal distribution form of probability density function, this experimental function is approximated and characteristics parameters of normal distribution variable including expectation μ and standard deviation $\sqrt{\upsilon}$ are determined. Figure III.5-2 shows kernel experimental probability density function (dashed line) and approximated probability density function (solid line).

Two curves are matched. Expected value and standard deviation are $\mu = 0,9969\text{cm}^2$, $\sqrt{\upsilon} = 0,0082\text{cm}^2$ and are also consistent with value calculated directly from denominator above.

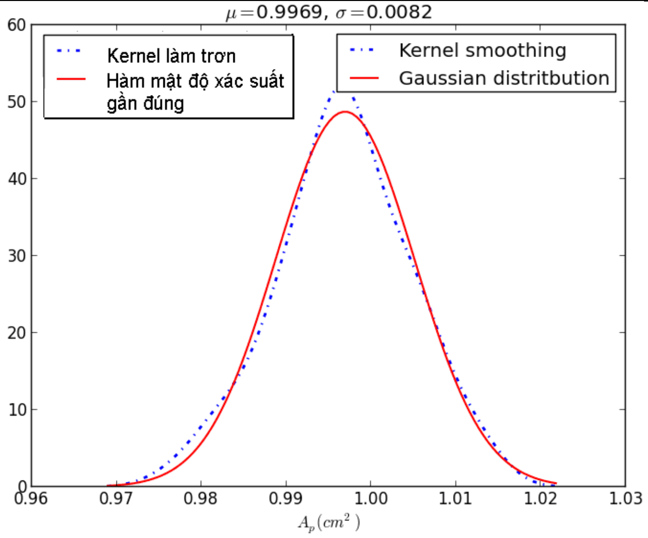


Figure III.5-2: Experimental probability density function (dashed line) and approximated probability density function (solid line) of tendon cross section random variable

III.5.3. Identification of random variable of tendon modulus of elasticity E_p

III.5.4. Identification of random variable of anchorage draw-in level δ_L

III.5.5. Identification of random variable of construction characteristic ε_L

Sections III.5.3 to III.5.5 presents procedures similar to that of identifying random variable of tendon cross section.

III.6. ACHIEVED RESULTS

Based on initial assessment of random variables related to prestressed slab design and affected to prestress losses that have normal distribution form or close to normal distribution form, Kernel method is used to identify these random variables based on statistics data collected from actual design and construction of post-tensioning concrete floor in Vietnam.

Capacity function is established with respect to crack control criteria for 3-span prestressed concrete floor designed according to AS 3600-2009.

When denominator value of a random variable is available, the random variable can be fully identified through identification of its probability distribution rule. Section III.3 presents two methods of identifying random variable (1) histogram method and (2) kernel density function estimation method.

Section III.3 also presents method of approximation of experimental probability density function based on least squares fitting method after identifying them by a probability distribution model in a similar form.

For evaluating reliability of structures, it is possible to simulate actions on the structure as random variables.

Section III.4 presents three methods to determine reliability of the problem and presents examples based on some methods such as indicator reliability β, Hasofer-Lind and Monte Carlo method. These methods give results that are comparable when random variables are in normal distribution forms.

If capacity function is not a specific mathematical analysis expression nor linear, it is not easy to apply indicator reliability β method and Hasofer-Lind method to carry out reliability assessment problems. The Monte Carlo simulation method is recommended for evaluating reliability of post-tensioning concrete floor with regard to crack control criteria.

Data of variable parameters such as elastic modulus, tendon cross section, anchorage draw-in level and construction effect factors are collected from laboratories and in Vietnam constriction practice.

Section III.5 presents results of these random variable identifications. A program is written in Python programming language.

CHAPTER IV: DEVELOPMENT OF PROGRAM CALCULATING RELIABILITY AND SURVEYING INFLUENCE OF PRESTRESS LOSSES TO RELIABILITY OF BONDED POST-TENSIONING CONCRETE FLOOR

From the results of identification of random variables presented in Section III.5, IV.1, this chapter introduces problem of reliability modeling. Section IV.2 presents the use of Monte Carlo method to evaluate reliability of post-tensioning concrete floor with respect to crack control criteria. Section IV.3 introduces economic-technical analyses influencing to reliability. Some conclusions are given at the end of the chapter.

IV.1. CALCULATE STRESS IN PRESTRESSED CONCRETE STRUCTURES AND APPLICATION OF MONTE CARLO METHOD TO DETERMINE RELIABILITY

IV.1.1. Flow diagram of stress calculation and capacity function

Capacity function is presented in Section III.1. Numerical method calculating stress in concrete and capacity function is shown in Figure IV.1-1:

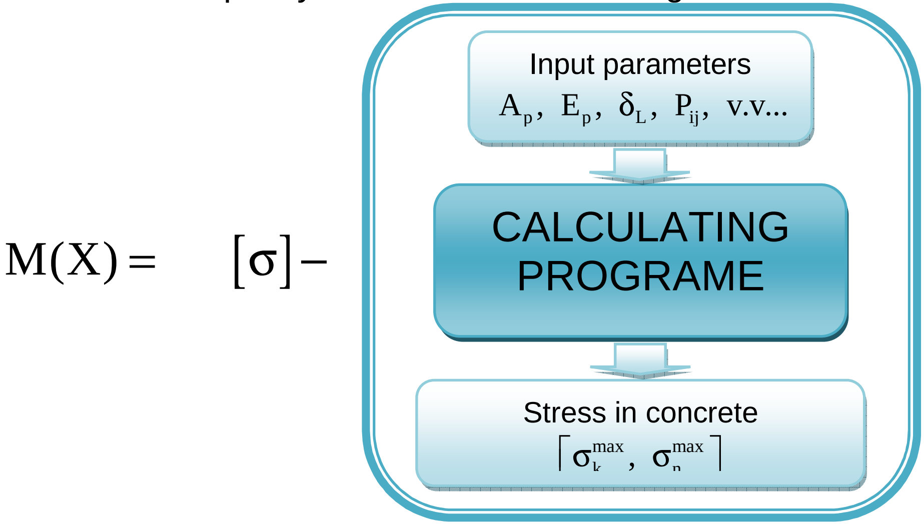


Figure IV.1-1: Flow diagram establishing capacity function

- Capacity function: Immediately after prestressing

  Compressive allowable stress: $M = 0,5f_{cp} - ABS\left[\min\left(\overline{\sigma^{*(TT)}}, \overline{\sigma^{*(TD)}}\right)\right];$

  Tensile allowable stress: $M = 0,6\sqrt{f_{cp}} - \max\left(\overline{\sigma^{*(TT)}}, \overline{\sigma^{*(TD)}}\right).$

- Capacity function: Service stage:

  Compressive allowable stress: $M = 0,5f_c^{'} - ABS\left[\min\left(\overline{\sigma^{(TT)}}, \overline{\sigma^{(TD)}}\right)\right];$

  Tensile allowable stress: $M = 0,6\sqrt{f_c^{'}} - \max\left(\overline{\sigma^{(TT)}}, \overline{\sigma^{(TD)}}\right).$

"CALCULATING PROGRAM" in Figure IV.1-1 is a process of prestress losses calculation, tendon selection and concrete stress calculation. Maximum tension and compression stresses in sections are selected as targets of the capacity function. The detailed flow diagram of " CALCULATING PROGRAM" is shown in Figure IV.1-2.

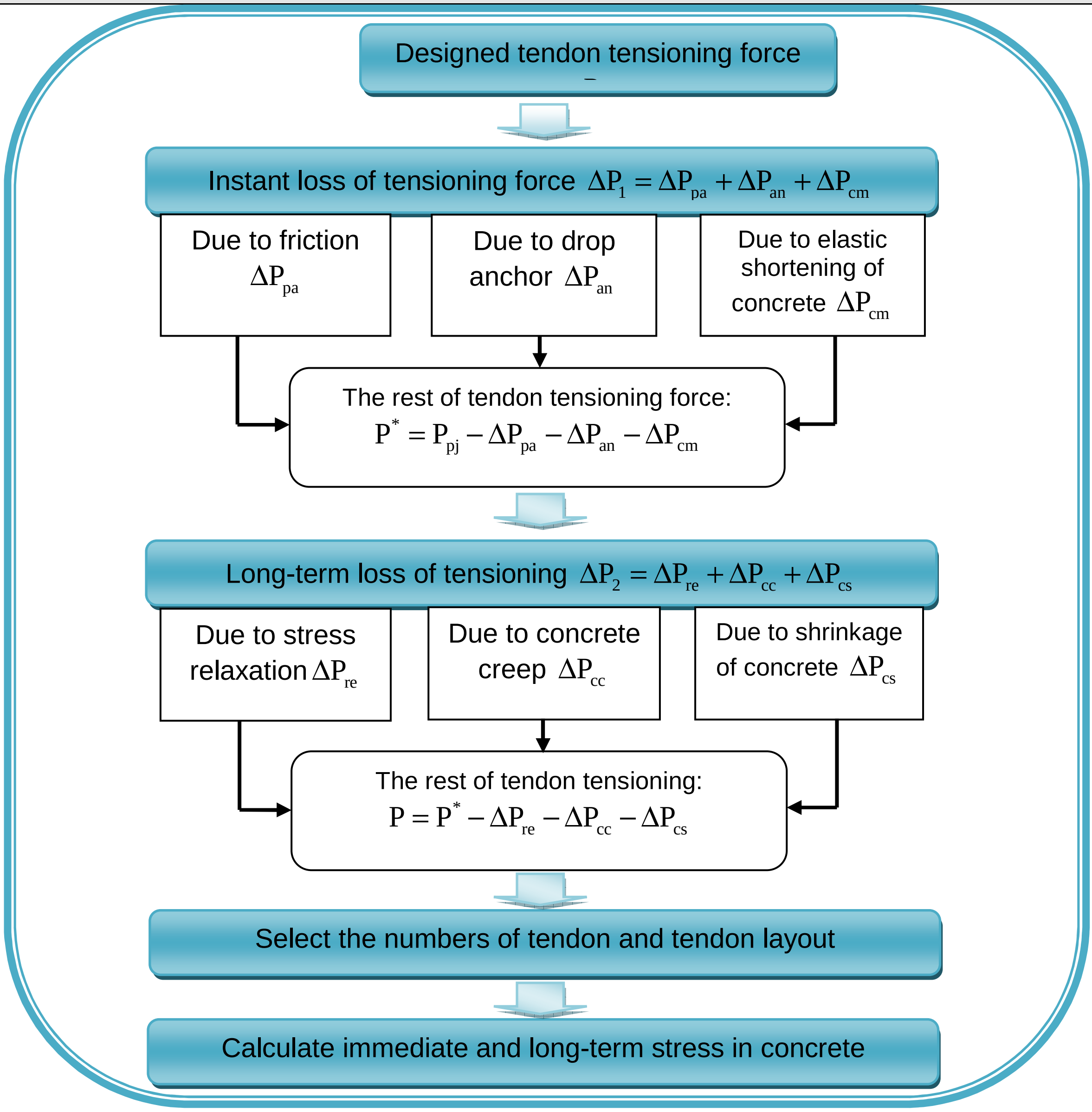


Figure IV.1-2: CALCULATING PROGRAM: Calculation of prestress losses, tendon selection and arrangement, checking tensile and compressive stress in concrete

IV.1.2. Flow diagram of reliability calculation

Some factors are considered in the research, including cross section and modulus of elasticity of tendon, anchorage draw-in level and construction effect factors. These parameters represent random nature of considered quantities that are simulated by the random variables (Section III.5). On the basis of determining input random vector $X = \{A_p,\ E_p,\ \delta_L,\ \varepsilon_L\}$ and capability function $M(X)$, stochastic model and Monte Carlo simulation is developed and shown in Figure IV.1-3. Safety conditions of bonded post-tensioning concrete floor structure with respect to crack control criteria are as follows:

- Immediately after prestressing

  Compressive allowable stress: $M = 0,5f_{cp} - ABS\left[\min\left(\overline{\sigma^{*(TT)}}, \overline{\sigma^{*(TD)}}\right)\right] \geq 0$;

  Tensile allowable stress: $M = 0,6\sqrt{f_{cp}} - \max\left(\overline{\sigma^{*(TT)}}, \overline{\sigma^{*(TD)}}\right) \geq 0$.

- Service stage:

  Compressive allowable stress: $M = 0,5f_c^{'} - ABS\left[\min\left(\overline{\sigma^{(TT)}}, \overline{\sigma^{(TD)}}\right)\right] \geq 0$;

  Tensile allowable stress: $M = 0,6\sqrt{f_c^{'}} - \max\left(\overline{\sigma^{(TT)}}, \overline{\sigma^{(TD)}}\right) \geq 0$.

Convergence condition of unsafety probability value P_f: the program determines P_f values after each 5000-times-interval of simulation. When numbers of value is greater than 20, the program calculates convergence indicator ζ, maximum value of difference between the final P_f minus previous (19) values, divided by P_f. Convergence condition is $\zeta \le 1,5\%$. Reliability is calculated by the program, namely RPS, as shown in Figure IV.1-3.

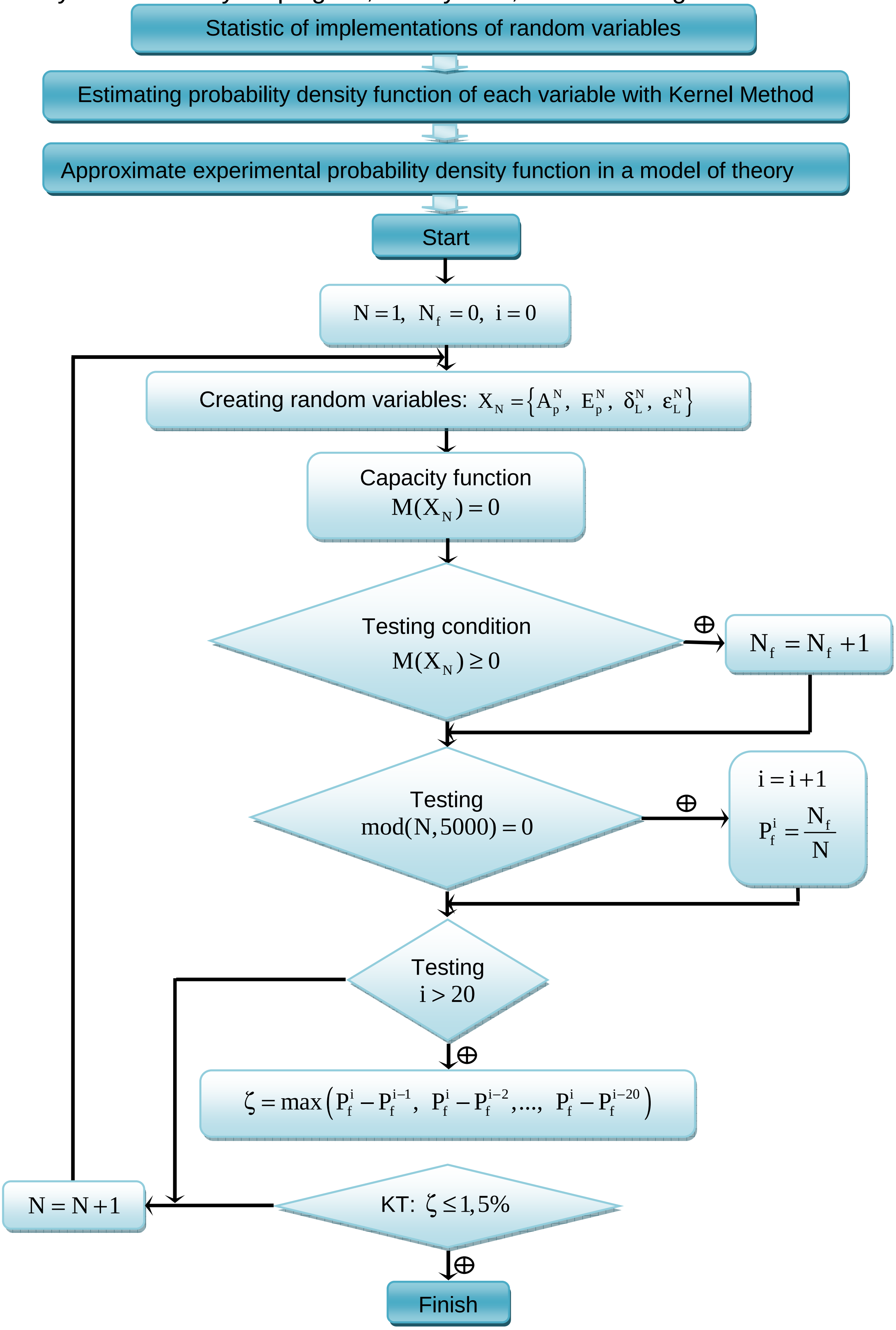


Figure IV.1-3: Flow diagram of random model and Monte Carlo simulation

IV.2. DETERMINATION OF RELIABILITY OF BONDED POST-TENSIONING CONCRETE FLOOR

IV.2.1. Structural design with determinately parameters

This section presents six (06) post-tensioning concrete floor designs for an office building type and a condominium building with design data shown in Table IV.2-1.

Table IV.2-1: Input parameters for 06 design examples

N^0	Parameter	Office building			Condominium		
		Type 1	Type 2	Type 3	Type 1	Type 2	Type 3
1	Equal 3 span floor (m)	7,5	9,0	12,0	7,5	9,0	12,0
2	Flooring strip width (m)	3,75	4,5	6,0	3,75	4,5	6,0
3	D_S floor thickness (mm)	200	230	330	210	240	340
4	Self-weight (daN/m^2)	500	575	825	525	600	850
5	Live load (daN/m^2)	200	200	200	150	150	150
6	Total characteristic loads (daN/m^2)	831	906	1156	1056	1131	1381
7	The largest deflection of tendon h (mm)	108	138	238	118	148	248

For each design, the considered results are stress in concrete corresponding to selected floor thickness $\mathrm{D_s}$ and numbers of tendon N.

IV.2.2. Determination of safety probability with respect to crack control criteria

Based on six (06) original designs presented in section IV.2.1, safety probability of the design in regard to crack control criteria is determined. This is implemented by Monte Carlo (MC) simulation as shown in Figure IV.1-3 on the basis of creating implementations of random variables identified in the previous section.

Figure IV.2-1 shows convergence of safety probability in MC simulation for a 7.5m 3-span office floor.

The probability value converged after about 550000 loops, is $\mathrm{P_s} = 0,99984$.

Result and comments: The derived safety and unsafety probability of 06 design examples are summarized in table IV.2-14.

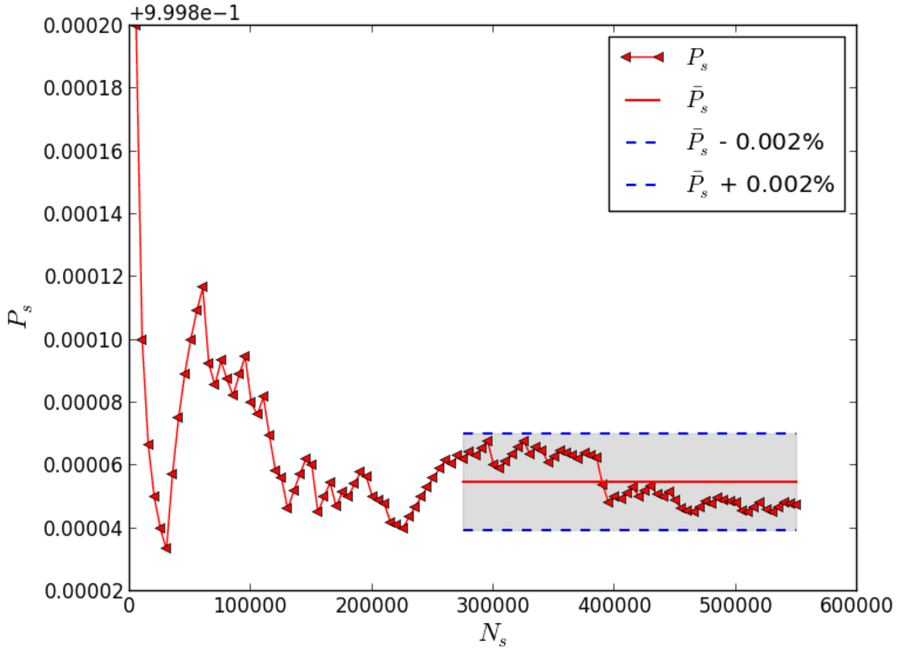


Figure IV.2-1: Convergence of safety probability, 7.5m-span floor - Office Building

Table IV.2-14: Safety probability assessment

	Building types and floor spans					
	3 span office floor			3 span condominium floor		
	7,5m	9,0m	12,0m	7,5m	9,0m	12,0m
Design stress σ, MPa	3,0773	3,2192	3,0673	3,1027	3,1504	3,1206
Allowable stress $[\sigma]$, MPa	3,3941	3,3941	3,3941	3,3941	3,3941	3,3941
Ratio $\sigma/[\sigma]$, %	90,67	94,85	90,37	91,41	92,82	91,94
safety probability P_s	0,99984	0,99174	0,99867	0,99880	0,99457	0,99491
Unsafety probability P_f	0,00016	0,00826	0,00133	0,00120	0,00543	0,00509
Numbers of convergence loop	550000	280000	370000	340000	190000	235000

As shown in the Table IV.2-14, for each choice of different initial deterministically design stress, safety probability (reliability) is different to each other. For considered examples, if design stress is from 90% to 95% of the allowable stress, unsafe probability is about 0.012% to 0.826 %.

The question is that for a specific problem, how to select design stress to satisfy a given safety probability. Section IV.2.3 presents results of safety probability determination for design problems with variations of design stresses.

IV.2.3. Effects of design stress variation on reliability

For each design problem presented in section IV.2.1, design stresses are chosen differently by mean of changing floor thickness.

Safety probability is determined for each obtained design stress. Variation of reliability is evaluated according to changes of design stresses.

Figure IV.2-7 shows relationship between stress and safety probability for a 7.5 m 3-span office floor.

It can be seen that, with design stresses of $90,67\%$, $97,26\%$, $121,09\%$ of allowable stresses, unsafety probabilities are $0,00\%$, $2,06\%$ and $99,88\%$, accordingly.

Results and Comments: From the results shown in Section IV.2.3 for each specific problem, design stress can be easily selected according to a given safety probability. However, results also indicate that if design stress is close to allowable stress, unsafety probability is quite high, approximately about 5% to 8%.

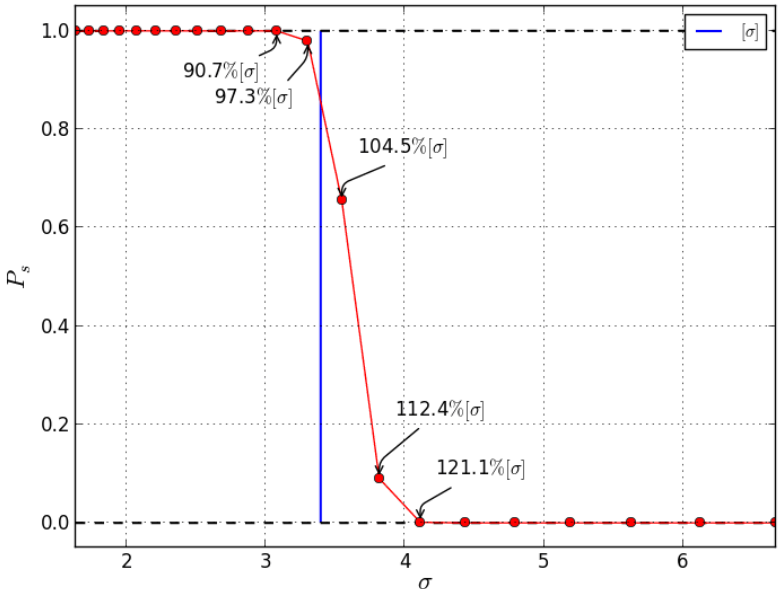


Figure IV.2-7: The relationship between stress and safety probability, 7.5m span floor – Office building

In practice, design stress is often chosen close to allowable stress. It needs to have measures reducing unsafety probability, even if design stress is selected close to allowable stress. One of solutions is to increase tendon prestressing force.

Section IV.2.4 presents results of determination of safety and unsafety probability when changing tendon prestressing force.

IV.2.4. Effects of tendon prestressing force P_{pj} on reliability

For each of 06 design problems presented in Section IV.2.1, design stresses are chosen approximately about 95%, 100% and 105% allowable stress, by mean of changing floor thickness.

For each of 03 design stress values, tendon prestressing forces are changed by $1,01P_{pj}$, $1,02P_{pj}$, $1,03P_{pj}$, $1,04P_{pj}$ and $1,05P_{pj}$, accordingly. Safety probability corresponding to each prestressing force is assessed to evaluate reliability variation with changes of prestressing forces.

Figure IV.2-13 shows the relationship between the magnitude of tendon prestressing forces and safety probabilities for 7.5 m 3-span office floor.

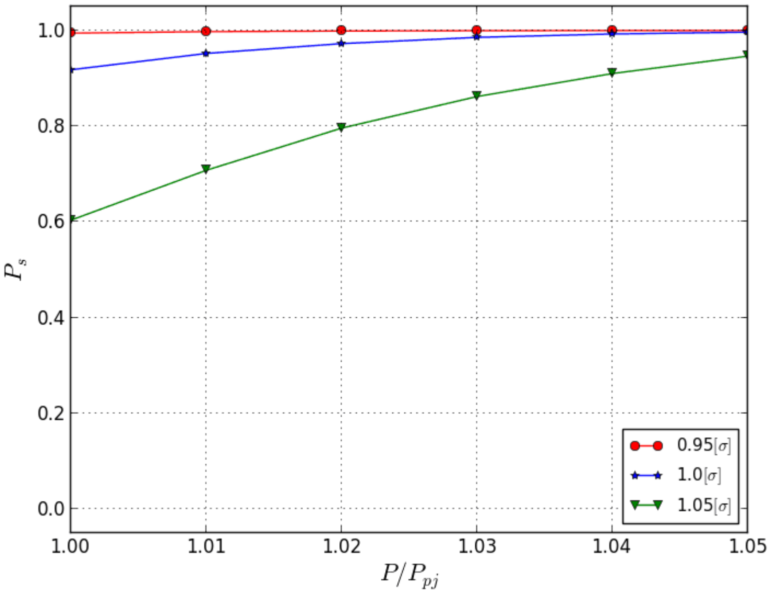


Figure IV.2-13: The relationship between tendon prestressing force and safety probability of 7.5m span floor - Office building

Results and comments: It can be shown from the analysis results that if design stresses are selected close to or exceed allowable stress, unsafety probabilities P_f are quite high. The change of tendon prestressing force P_{pj} can significantly reduce unsafety probability P_f. With design stress equal to 105% allowable stress, if tendon prestressing force of P_{pj} unsafety probability of 9m 3 span post-tensioning concrete office floor is $P_f = 31,320\%$, if tendon prestressing force $1,05P_{pj}$, $P_f = 3,596\%$. For designs with stress close to allowable stress, it is recommended to adjust tendon prestressing force to keep a small unsafety probability.

IV.2.5. Effects of environmental temperature on reliability

A 7.5m 3-span post-tensioning concrete office floor design is considered. Temperature at construction area is taken as $T = 25^0C$. Safety and unsafety probability is determined according to the temperature varying from $T = 20^0C$ to $T = 30^0C$ (Figure IV.2-19 and Table IV.2-19).

It can be shown form the Figure IV.2-19 and Table IV.2-19 that temperature significantly influences to unsafety probability of building. With initial temperature of $T = 25^0C$, unsafety probability is $P_f = 0,000162$. As temperature decreases 1^0C to $T = 24^0C$, unsafety probability reduces to $P_f = 0,00008$; when temperature increases 1^0C to $T = 26^0C$, unsafety probability is $P_f = 0,000317$.

Recommendations: It is necessary to consider environmental temperature, which is measured on site, for designing of floor structures.

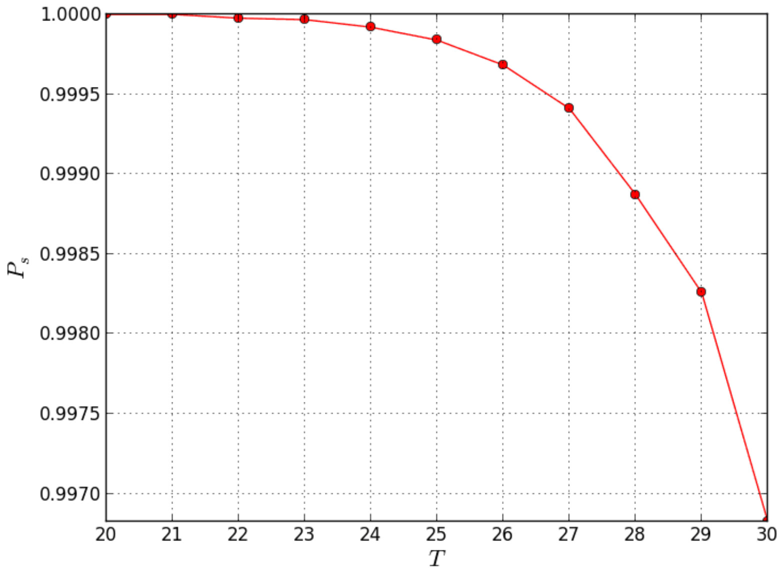


Figure IV.2-19: The relationship between environmental temperature and safety probability of 7.5m span floor - Office building

Table IV.2-19: Unsafety and safety probability with changes of environmental temperature, 7.5m 3-span post-tensioning concrete office floor

Probability	**Environmental temperature changes from** $T = 20^0C$ **to** $T = 30^0C$						
	20	22	24	25	26	28	30
P_s	1	0,99998	0,99992	0,99984	0,99968	0,99887	0,99683
P_f	0	0,00002	0,00008	0,00016	0,00032	0,00113	0,00317

IV.2.6. Effects of humidity on reliability

According to the Vietnam construction regulation, common value of annually humidity over Vietnam territory is about 70%, corresponding with coefficient $k_4 = 0,5$. However, almost office buildings or commercial centers use air conditioning daily and in years. Humidity in room is much lower than outdoor humidity. This directly affects prestress losses due to shrinkage and creep of concrete.

A 7.5m 3-span post-tensioning concrete office floor is considered in the study. Initial design humidity is 70%, with $k_4 = 0,5$. Humidity is changed from 70% to 40%, $k_4 = 0,5$ increases to $k_4 = 0,7$ accordingly. Safety and unsafety probability is determined corresponding to each of k_4 values (Figure IV.2-20 and Table IV .2-20).

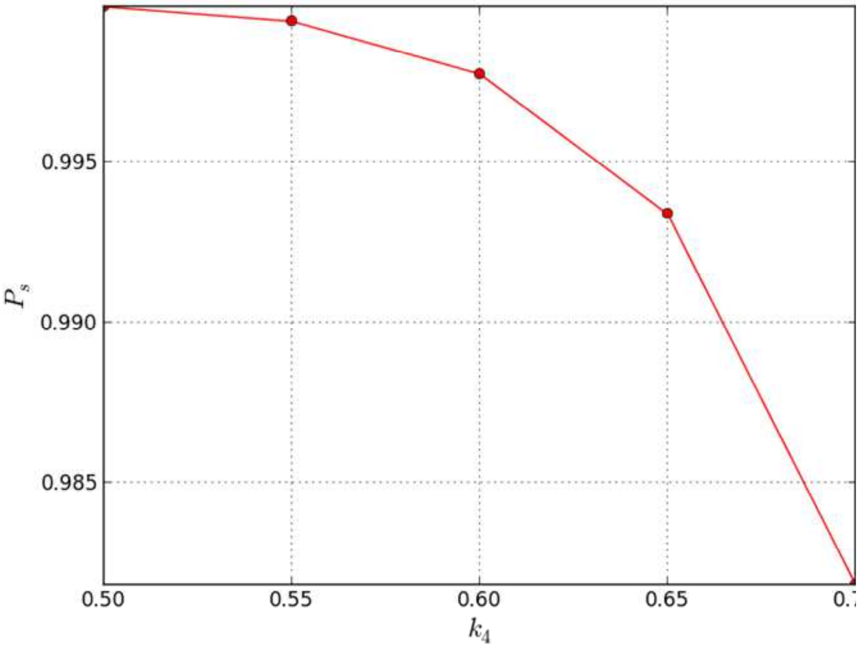


Figure IV.2-20: The relationship between environmental humidity and safety probability of 7.5m span floor - Office building

Table IV.2-20: Safety and unsafety probability when changing environmental humidity (7.5m 3-span post-tensioning concrete office floor)

Probability	Environmental humidity changes from 70% to 40%, $k_4 = 0,5$ increases to $k_4 = 0,7$				
	$k_4 = 0,5$	$k_4 = 0,55$	$k_4 = 0,6$	$k_4 = 0,65$	$k_4 = 0,7$
P_s	0,999858	0,999404	0,997758	0,993371	0,981795
P_f	0,000142	0,000596	0,002242	0,006629	0,018205

From the Figure IV.2-20 and Table IV.2-20, it is found that environmental humidity factor has major effects on unsafety probability of buildings. If the original environmental humidity is 70% ($k_4 = 0,5$), unsafety probability is acceptable $P_f = 0,000142$. However if humidity in the room reduces to 50% or below ($k_4 = 0,65$) during operation period, unsafety probability significant increases to $P_f = 0,006629$.

Recommendations: It is necessary to consider environmental humidity in actual usage condition when designing of post-tensioning concrete floor structures.

IV.2.7. Effects of basic stress relaxation on reliability

IV.2.8. Effects of sagging tolerance of tendon in construction on reliability

Section IV.2.7 and IV.2.8 presents determination of safety probability for a 7.5m 3-span post-tensioning concrete office floor in consideration of changes of basic stress relaxation and deflection of tendon. It is shown that reliability is considerably influenced by these factors. It is recommended to conduct sufficient data of basic stress relaxation for subsequent studies, as well as strict regulations related to post-tensioning concrete floor construction and acceptance, especially reinforcing steel installation, is important.

IV.2.9. Reliability assessment of developed program results

This section evaluates reliability the developed program in term of following issues:

- Compare prestress losses and stress in concrete with other common programs. The results are comparable.
- Checked accuracy of parameter identification method based on probability density function associated with actual statistics data. The results are comparable.
- Compare results obtained from Monte Carlo method with those from other methods such as reliability indicator β and Hasofer – Lind. The results are matched.

The developed program is reliable.

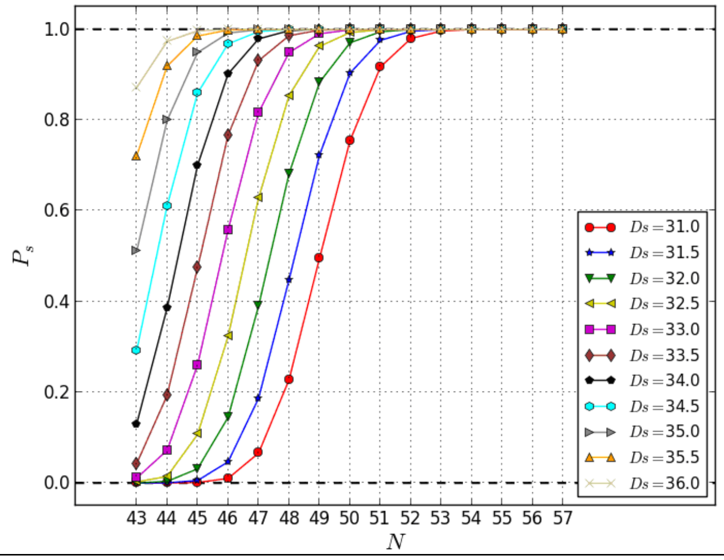
IV.3. ECONOMIC – TECHNICAL ANALYSES

Results of the researches on reliability of prestressed concrete floor structure indicate technical issues need to be considered in design and construction. However, the economic issue is of concern in any design. The design optimization based on consideration of reliability is mentioned, so that the design should be made to ensure given reliability with reasonable cost. Technical and economic analysis of designs is presented in Section IV.3 on the basic of method presented Section IV.2.1.

This section analyzes effects of design on reliability and cost of a 12m 3-span condominiums and office building floor.

IV.3.1. Effects of N and D_s on reliability and cost

Figure IV.3-1a shows dependence of reliability on D_s and N for a floor design of a 12m 3-spans office building.



IV.3-1a: Reliability of 12.0 m 3-span office building floor with different choices of floor thickness D_s and number of tendon N

Figure IV.3-1b shows dependence of structure cost on D_s and N for a floor design of a three 12m-spans office building.

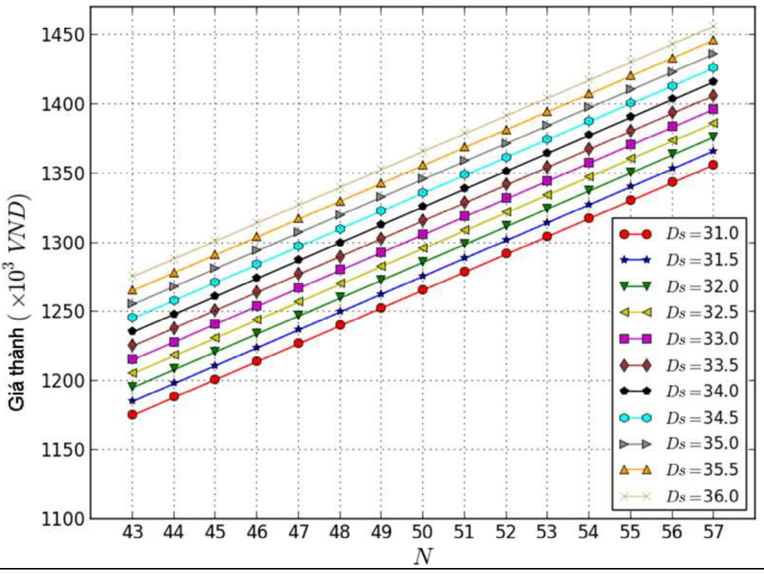


Figure IV.3-1b:Cost per m2 of 12.0m 3-span office building floor with different choices of floor thickness D_s and number of tendons N

IV.3.2. Table of reliability and cost (depend on N and D_s)

This section presents reliability and cost depending on choices of N and D_s in tubular forms, for a floor design of a 12m 3-span office building.

IV.3.3. Remarks

Through technical and economic analysis it is shown that, for each specific case, designer can choose different options of floor thickness D_s and number of tendons N. Regarding to relationship of reliability and economic issue, designer can also determine reasonable design alternatives.

The developed technical-economic analysis program can help designers conveniently evaluating reliability with respect to crack control criteria, considering factors of cost, floor thickness and number of tendons.

However, the research has some limitations. Effects of rebar unit price changes and slab thickness on costs of vertical structural elements and foundations are out of scopes of the thesis.

Hence, further researches on effects of other factors on reliability of prestressed concrete floor are recommended. Factors such as limit deflection criteria, shear or punching criteria and durable criteria, etc. should be considered. These studies can provide adequately information to assess relationship between reliability and price.

IV.4. ACHIEVED RESULTS

Develop a program calculating prestress losses, stress in concrete (appendix 6) and reliability of bond post-tensioning concrete floor structure. Program language used is Python.

Apply the program to assess reliability of bonded post-tensioning prestressed concrete floor design with respect to crack control criteria. Determination of required loop of Monte Carlo simulation is considered on the basis of convergence of probability values that are determined according to a certain criteria.

Evaluate effects of prestress losses to reliability of bonded post-tensioning prestressed concrete floor structure (section IV.2.2 to section IV.2.8). Some comments and recommendations are as follows:

+ For each choice of different deterministically design stress, assessments of safety probability (reliability) give different results. With considered examples, if design stress is selected from 90% to 95% of allowable stress, probability of unsafety condition is about 0.012% to 0.826%.

+ For each of specific cases, with a given safety probability it is easy to determine design stress. From the calculated results it is also indicated that if design stress close to allowable value probability of unsafety condition is quite high, approximately 5 % to 10 %. Change of prestressing force P_{pj} can significantly reduce unsafety probability P_f. For designs that have stress close to allowable value, it needs to be considered to adjust prestressing forces in order to keep a small unsafety probability. The adjustment can be done only when the prestressing force is lower than ultimate value. If prestressing force is close or equal to the ultimate value designer should carefully determine design stress so that it is well less than allowable stress to ensure acceptable unsafety probability. In contrast, design stress can be selected close to allowable value provided that prestressing force is well below ultimate value.

+ Temperature and humidity has significant effects on reliability of structures. Therefore the factors should be considered in design stage and in operation. Particularly attentions should be made for structures subjected to full-time air conditioning over years.

+ Basic stress relaxation as well as tendon deflection tolerance also influence to reliability of structures. However, due to limitation of collected data the issue needs to be studied further.

+ It is possible to establish graphs and tables used for reliability assessment of bonded post-tensioning prestressed concrete floor design associated with corresponding cost, with respect to alternations of floor thickness and number of tendons. By this way designers can determine an optimal solution with regard to economic and technical factors.

CONCLUSIONS AND RECOMMENDATIONS

I. CONTRIBUTIONS OF THE RESEARCH

1. Develop capacity function with respect to crack control criteria of prestressed concrete floor designing according to AS 3600-2009. Considered

parameters are cross section of tendon A_p, tendon elastic modulus E_p, anchorage draw-in value δ_L; construction effect factor (ratio of actual elongation and design value) ε_L (section III.1).

2. Establish construction effect factor ε_L on basis of design elongation ΔL_{LT} and actual value ΔL_{TT} (section III.1.4).
3. Develop a program calculating prestress losses, stress in concrete (appendix 6) and reliability of bond post-tensioning concrete floor structure (appendix 7).
4. Carry out parametric studies of considered effect factors, including cross section of tendon A_p, tendon's elastic modulus E_p, anchorage draw-in value δ_L; construction effect factor ε_L on basis of data collected from laboratories and constructions in Vietnam (appendix 8). For quantitative assessment, some other factors are also examined such as temperature, humidity of environment, basic stress relaxation of tendon, sag of tendon.
5. Apply the developed program to assess relationship between cost and reliability of constructions. Based on this important information, rational designs could be determined (section IV.3)
6. Following results of reliability calculations and prestress loss effect assessments, recommendations of stress determination during design phase, prestressing forces during construction process and effects of environmental conditions during service period are clearly provided (section IV.2.3 to section IV.2.8).

II. RECOMMENDATIONS

1. The research can be extended to assess reliability of design problems with different criteria such as allowable deflection, shear strength, etc. ...
2. It is recommended that data such as basic stress relaxation of tendon, elastic modulus and strength of concrete should be sufficiently collected in order to deal with reliability assessment problems with respect to these parameters.

PUBLISHED RESEARCH WORKS

[1] Nguyen Xuan Chinh, Nguyen Chi Hieu. Assessment of the reliability and technical conditions of building structures under the signs of surface. Journal of Building Science and Technology No. 1/2012.

[2] Nguyen Xuan Chinh, Nguyen Chi Hieu. Assessment of the reliability and technical conditions of building structures under the signs of tensile surface. Journal of Building Science and Technology No. 2/2012.

[3] Nguyen Chi Hieu, Nguyen Xuan Chinh. Prestressed reinforced concrete structure in civil construction. Collection of scientific reports - National Conference on Science and Technology Building, 2001-2012 period.

[4] Nguyen Chi Hieu. loss of stress in design of post - tensioning prestressed reinforced concrete. Journal of Building Science and Technology No. 3+4/2013.

[5] Nguyen Chi Hieu, Nguyen Hoang Anh, Le Van Tu. Efficient of application of bond post tensioning prestressed reinforced concrete floor structure in civil construction. Collection Report - Scientific Conference 50th anniversary of establishment of Viet Nam Institute for Building Science and Technology, 2013.

[6] Nguyen Chi Hieu, Nguyen Hoang Anh, Nguyen Van Viet. Several issues should be noted in construction, acceptance bond post tensioning prestressed reinforced concrete floor structure. Collection Report - Scientific Conference 50th anniversary of establishment of Viet Nam Institute for Building Science and Technology, 2013.

[7] Nguyen Chi Hieu, Nguyen Xuan Chinh. Some notes on design, construction, acceptance, use and maintenance of prestressed reinforced concrete structure in civil construction. Review of Ministry of Construction No. 3/2014.

[8] Nguyen Chi Hieu. Influence of construction to reliability of pre-stressed reinforced concrete floor. Journal of Structural Engineering and Construction Technology, No 14, I-2014.