Załącznik /Appendix 4

Autoreferat dotyczący działalności naukowo-badawczej, dydaktycznej i organizacyjnej w języku angielskim / Summary of professional accomplishments

Contents:

1. Name and surname

Ireneusz Marzec

2. Diplomas held, scientific degrees with the indication of the name, place and year in which they were acquired, as well as the title of the doctoral dissertation

1. 23.10.2003. Master of Science, discipline: Civil Engineering, specialization: Structural Engineering. Gdansk University of Technology, Faculty of Civil Engineering.
2. 11.03.2009. PhD Degree in Technical Sciences, discipline: Civil Engineering. Gdansk University of Technology, Faculty of Civil and Environmental Engineering. Dissertation's title: Application of elasto-plastic model with stiffness degradation and non-local softening to describe behaviour of concrete members under cyclic loading. Supervisor: Prof. Ph.D., D. Sc., Eng. Jacek Tejchman. Reviewers: Ph.D., D. Sc., Eng. Jerzy Pamin, Professor of CUT, Ph.D., D. Sc., Eng. Jarosław Górski.

3. Information about employment in academic/research institutions

1. 15.11.2004-30.11.2005 – research assistant (part time, 0.2 of full time): Gdansk University of Technology, Faculty of Civil and Environmental Engineering.
2. 01.12.2005-31.08.2006 – research assistant (part time, 0.5 of full time): Gdansk University of Technology, Faculty of Civil and Environmental Engineering.
3. 01.09.2007-31.03.2009 – research assistant (full time): Gdansk University of Technology, Faculty of Civil and Environmental Engineering.
4. 01.04.2009-31.03.2017 – assistant professor (full time): Gdansk University of Technology, Faculty of Civil and Environmental Engineering.
5. from 01.04.2017 – senior lecturer (part time, 0.5 of full time): Gdansk University of Technology, Faculty of Civil and Environmental Engineering.

4. Indication of the achievement resulting from article 16, paragraph 2 of the Act of 14 March 2003 on academic degrees and title and degrees and title in the arts

a. Title of the scientific achievement

Numerical modeling of reinforced concrete and concrete elements using constitutive laws for concrete with non-local softening

b. Publications included in the scientific achievement

1. **Marzec I.**, Tejchman J. 2012. Enhanced coupled elasto-plastic-damage models to describe concrete behaviour in cyclic laboratory tests: comparison and improvement. *Archives of Mechanics* 64(3), 227-259.
2. **Marzec I.**, Tejchman J. 2013. Computational modelling of concrete behaviour under static and dynamic conditions. *Bulletin of the Polish Academy of Sciences-Technical Sciences* 61(1), 85-95.
3. **Marzec I.**, Skarżyński Ł., Bobiński J., Tejchman J. 2013. Modelling reinforced concrete beams under mixed shear-tension failure with different continuous FE approaches. *Computers and Concrete* 12(5), 585-612.
4. **Marzec I.**, Tejchman J. 2014. An elasto-plastic constitutive model with non-local softening and viscosity to describe dynamic concrete behaviour. *Computational Modelling of Concrete Structures*, 1, 127-137, CRC Press, Taylor and Francis Group, London, ISBN 978-1-138-00145-9.
5. **Marzec I.**, Tejchman J., Winnicki A. 2015. Computational simulations of concrete behaviour under dynamic conditions using elasto-visco-plastic model with non-local softening. *Computers and Concrete* 15(4), 515-545.
6. Skarżyński Ł., **Marzec I.**, Tejchman J. 2017. Experiments and numerical analyses for composite RC-EPS slabs. *Computers and Concrete* 20(6), 689-704.
7. Skarżyński Ł., **Marzec I.**, Drąg K., Tejchman J. 2018. Numerical analyses of novel prefabricated structural wall panels in residential buildings based on laboratory test in scale 1:1. *European Journal of Environmental and Civil Engineering* 1-33, doi: 10.1080/19648189.2018.1474382.

8. Suchorzewski J. **Marzec I.**, Tejchman J., Korol E. 2018. Investigations of strength and fracture in RC beams scaled along height. *Computational Modelling of Concrete Structures* 651-661, CRC Press, Taylor and Francis Group, London, ISBN 978-1-138-74117-1.
9. **Marzec I.**, Tejchman J., Mróz Z. 2019. Numerical analysis of size effect in RC beams scaled along height or length using elasto-plastic-damage model enhanced by non-local softening. *Finite Elements in Analysis and Design* 157, 1-20.

In total 7 publications in journals included in the Journal Citation Reports (JCR) database.

c. Discussion of the above mentioned scientific work and the obtained results, including evaluation of their potential use

Concrete is a quasi-brittle material. The behavior of concrete can be treated as linear only in a small range of deformation, in the remaining part it is strongly non-linear. When the load-bearing capacity is reached, there exists a significant and sudden drop in stresses under both tension and compression. This softening behavior is accompanied by the concentration of deformations in small zones (thin micro-cracks are created, known as deformation zones or fracture process zones (FPZ)), which with further increase of deformation develop into a discrete macro-cracks. Within continuum mechanics, one of the basic methods of describing cracks is to describe them in a smeared way using the location zones with certain width. As constitutive models an elasto-plastic formulations, damage continuum mechanics or combined formulations are used. However, using the classical constitutive laws with softening within the finite element method leads to incorrect results. The calculated force-displacement curves depend on the assumed FE mesh, and the strains are concentrated in thin bands with the width of one finite element. To prevent this pathological mesh-dependency, it is necessary to extend the classical constitutive models by introducing the so-called regularization. One of the possibilities is the introduction of the non-local theory. The general idea of this theory is to replace the local variables of the model determined in a given material point with their non-local counterparts, obtained through a spatial averaging operation in the vicinity of the considered point. As a consequence, the characteristic length of the microstructure is introduced into the constitutive equations. The use of the characteristic length ensures the mesh-independence of the numerical results. In addition, it also allows to simulate the deterministic size effect. It should be noted, that such advanced regularization techniques are not available in commercial programs using the Finite Element Method (FEM). Thus, to properly reflect the failure mechanism of concrete and reinforced concrete elements, it is necessary to correctly predict the formation and growth of the strain localization zones (their shape, number, spacing and position). When modeling reinforced concrete elements, it is also important to take into account the contact law between reinforcement bars and concrete.

As part of my doctoral thesis, I have analyzed existing coupled models in order to check their ability to proper reflect both: the plastic deformations and stiffness degradation, and enriched them with characteristic length of the microstructure. I used a coupled elasto-plastic model with stiffness degradation according to Pamin and de Borst (Pamin J., de Borst R., 1998. Simulation of crack spacing internal length parameter. Arch. App. Mech., 68(9), 613–625) and two-surfaces coupled model with degradation defined in terms of plasticity according to Hansen and Wilam (Hansen E., 2000. A two-surface anisotropic damage/plasticity model for plain concrete. PhD Thesis, University of Colorado at Boulder, Boulder). Both constitutive laws have been enriched with a characteristic length in order to properly regularize the boundary value problem. The primary goal of my scientific research after my doctoral thesis was the further development of constitutive laws (within continuum mechanics) for concrete under quasi-static and dynamic loads. I have introduced and presented an improved coupled elasto-plastic-damage model with stiffness degradation and non-local softening for concrete under quasi-static and cyclic loading conditions. It is a coupled formulation combining isotropic damage with elasto-plastic criteria defined in effective stress space. I also proposed a modifications of the elasto-plastic and elasto-visco-plastic constitutive models to describe concrete behavior under dynamic loading conditions. All presented and implemented models for concrete were enriched with characteristic length in terms of integral non-local approach. All numerical simulations were performed in the ABAQUS software. Due to the nature of the research included in the scientific achievements in the period after doctoral thesis, their scope can be divided into two separate issues:

A) an improved coupled elasto-plastic-damage model with stiffness degradation and non-local softening to describe behaviour of concrete and reinforced concrete elements under quasi-static and cyclic loading,

B) an improved elasto-visco-plastic model with non-local softening to describe concrete behaviour under dynamic loading,

A. An improved coupled elasto-plastic-damage model with stiffness degradation and non-local softening to describe behaviour of concrete and reinforced concrete elements under quasi-static and cyclic loading

The classic elasto-plastic formulations with softening are able to properly reflect the formation and development of permanent deformations in concrete (plastic deformation). In turn, material models within damage continuum mechanics introduce to the material description the concept of effective stresses and stiffness degradation due to damage growth. However, in case of concrete, both these phenomena (plastic deformations and stiffness degradation) occur simultaneously. Thus, this is the motivation for application of coupled models which combining in one formulation the characteristics of elasto-plastic models and damage one. Based on the experience gathered at the stage of creating the doctoral dissertation and further research work on coupled constitutive formulations, I proposed my own coupled model to describe the concrete behaviour under a quasi-static monotonic and cyclic loading.

In the first article (item 4.b.1) I compared three different coupled models, each of which represented a different concept of coupling between plasticity and damage. The first, most common method is to define elasto-plasticity in terms of effective stress space. In this approach, damage depends on the strain tensor and does not directly influence plasticity. Despite of the simplicity, this type of models are characterized by high efficiency. The second method consists in defining the damage in a form analogous to the elasto-plastic constitutive law. Thus, usually we have here models with two failure surfaces. Under compression, it is usually a classical elasto-plastic function, whereas under tension a load function with a damage parameter defined in the spirit of plasticity. The last concept of combining both formulations consists in an explicitly relate the damage parameter to plastic strain tensor. Then, in the same paper, I presented my own concept of the coupled model. To describe the concrete behavior in elasto-plastic domain, I used the failure surface with Drucker-Prager (compression) and Rankine (tension) criteria. I assumed that elasto-plasticity is defined in the effective stress space, and damage is introduced using the strain equivalence hypothesis. I assumed isotropic damage formulation with the equivalent strain measure according to Mazars (1986).

Damage growth under compression and tension was independently described by two different exponential function. In turn damage activation (both in tension and compression) was governed solely with aid of one triggering parameter. In addition, the damage definition was enriched with two scaling functions and one stress weight function according to Lee and Fenves (1998). As a consequence, the presented constitutive model allows also to simulate the "stiffness recovery" effects during loads reversals (tension/compression). In order to introduce the regularization, I assumed the non-local theory in integral form: the equivalent strain measure was replaced by its non-local counterpart. I used the Gauss weighting function to describe the influence of surrounding points. The model was verified with aid of experimental data for concrete specimens under compression and bending. The data from uniaxial cyclic compression test and three- and four-point cyclic bending tests were used. The results of numerical simulations were in good compliance with experimental data (items 4.b.1 and 4.b.2). The ultimate force, the shape of the load-displacement curve in the softening regime as well as the damage growth and increase of plastic deformation were correctly reproduced. Due to the presence of characteristic length the model managed also to satisfactorily reproduce the size effect in bending concrete beams (with notch) of various sizes.

Another paper (item 4.b.3) presented the results of numerical simulations for bending short reinforced concrete beams without transverse (shear) reinforcement. As a experimental data, the Walraven and Lehwalter (1994) work was used, in which four geometrically similar beams with different dimensions were examined. Four different material laws enriched with the characteristic length of microstructure were used to describe the concrete behaviour. Apart from the coupled model, the classical elasto-plastic law, the isotropic damage model and the anisotropic smeared crack model were also used. In turn, to simulate the behaviour of steel bars, an elastic-perfectly plastic constitutive model was assumed. For describing the interaction between concrete and reinforcement, a bond-slip law proposed by Dörr was assumed. All applied constitutive laws showed comparable, satisfactory agreement with respect to the calculated ultimate vertical forces for beams of different heights. In addition, all models correctly reproduced the size effect observed in experiments. Discrepancies between presented models concerned mainly the crack pattern. The best results were obtained for the elasto-plastic constitutive law and the coupled elasto-plastic-damage model. In case of anisotropic smeared crack model the agreement was average. The worst results were obtained within isotropic damage mechanics. In addition, spacing of the location zones obtained in numerical simulations (elasto-plastic and coupled model) corresponded well with the average experimental crack spacing, but were also much smaller than the values calculated from available analytical formulas.

The next stage (item 4.b.6) concerned 3D numerical simulations for full-size prefabricated floor slabs. Reference data has been taken from the experimental research program for elements of the prefabricated residential building system "Sewaco" conducted in the Department of Building Structures and Material Engineering under the supervision of prof. J. Tejchman. To describe the concrete, a non-local coupled elasto-plastic-damge model and non-local elasto-plastic formulation was used. For steel bars an elastic-perfectly plastic constitutive model was assumed. The bond-slip between concrete and reinforcement was described by the law proposed by Dörr. Finally, the expanded polystyrene (EPS) core was modeled as the elastic 3D elements. In calculations, the effect of fracture energy and contact stiffness between steel and concrete was analyzed. The main purpose of the simulation was a detailed analysis of the failure mechanism. The influence of the different parameters of both models on position and inclination of the critical diagonal localized zone was investigated. The results of numerical simulations were also compared with analytical formulas. There was a good agreement between the numerical results and experimental outcomes with respect to the failure mechanism, the calculated ultimate vertical force as well as the position and shape of the critical diagonal localized zone. The differences between two numerical models concerned mainly the shape and inclination of the inclined shear zone and the overall number of location zones.

The continuation of the works presented in item 4.b.6 was 3D simulations of full-size prefabricated wall panels (item 4.b.7). Again, as the reference data, the experimental research program for elements of the prefabricated residential building system "Sewaco" conducted in the Department of Building Structures and Material Engineering under the supervision of prof. J. Tejchman was used. In the numerical simulations, the same constitutive models as for floor slabs were assumed. Material parameters were also taken from previous simulations. The most complex type of prefabricate element was used for the FEM analysis. Wall panel with window and door openings. The numerical model included both longitudinal reinforcement and stirrups. Additionally, in analysis two simple approaches to dimensioning RC structures: the frame model (FM) and truss wall model (TWM) were used to calculate load-bearing capacity of various types of wall panels. The calculated maximum load-bearing capacities were in good accordance with experimental data. In addition, advanced numerical models (non-local coupled model and non-local elasto-plastic model) satisfactorily reflected the crack pattern. The numerically obtained pattern of the localized zones in general coincided with the experimentally observed cracks. Due to the complex geometry and the inability to apply any simplifications (e.g. the use of symmetry), the important aspect of numerical simulations concerned the number of finite elements used and the time cost of simulation. This is particularly important for models with non-local softening. In the non-local approach, the integrative algorithm generally requires gathering information from all surrounding elements in every computational step. Consequently, for simulations with the so-called full integration scheme, the total time of one simulation was about 3-4 weeks. Application of the so-called reduced integration scheme (with taking into account only neighbor points at a distance of three characteristic lengths) allowed to shorten the calculation time of one simulation to about 9 days without significant influence on the obtained results. In simulations I have also checked another type of regularization technique - scaling the fracture energy (i.e. crack band approach). The use of this technique allowed for further reduction of calculation time. Good agreement was also achieved with respect to the calculated load-bearing capacity. On the other hand, the agreement with respect to obtained localized zones was significantly worse in comparison with the non-local approach. Critical localized zones were not reproduced correctly. Obtained results confirmed the conclusions of other researchers, that the above-mentioned crack band approach does not allow to obtain completely mesh-independent results for reinforced concrete elements, in contrast to the non-local approach.

The last two publications (item 4.b.8 and item 4.b.9) summarize the work on the coupled elasto-plastic-damage model. For verification, the results of experimental tests of reinforced concrete beams conducted in the Department of Building Structures and Material Engineering under prof. J. Tejchman supervision were used. A characteristic feature of tested elements was the use of reinforced concrete beams with independently scaled height and length. As a consequence, beams with different shear heights were characterized by completely different failure mechanisms. For beams with relatively small height the flexural failure mechanism with plastic yielding of reinforcement was observed. In turn, for higher beams the brittle shear failure mechanisms were observed, characterized by formation of inclined critical crack leaded to failure. In addition, for brittle shear two different modes occurred: shear with dominant normal diagonal crack displacements (so-called diagonal shear-tension failure) and shear with significant both tangential and normal diagonal crack displacements (so-called diagonal shear-compression failure) with a huge increase of the ultimate shear strength supported by an internal arch action. First mode occurs for medium height beams, in turn the second mode is characteristic for the highest beams. The results of preliminary numerical simulations with a non-local coupled elasto-plastic-damage model were not fully satisfactory. In particular, the numerically obtained location zones did not adequately reflect the failure mechanisms occurring in medium and very high beams. In order to improve the efficiency of the model, I introduced modification - the damage growth under compression and tension was independent to each other. Instead of one threshold parameter, I assumed two additional variables that independently controlled solely compression and tension damage growth. In addition, both variables are calculated based on the same threshold parameter using the stress weight function. Thus, the modification did not increase the overall number of independent material parameters necessary for calibration. In addition, in the FEM simulations, a more sophisticated bond-slip law for interaction between steel and concrete was used. The relationship between the bond shear stress and slip followed CEB-FIP Code. This bond-slip law describes 4 different phases by taking hardening/softening into account in the relationship. FE-results using the improved combined model showed a very good accordance with experimental data. All failure mechanisms occurring in the beams were correctly reflected. In addition, the model accurately reproduced the size effect. In the simulations I also analyzed the influence of tensile and compressive fracture energy as well as the different stiffness of contact between steel bars and concrete.

My non-local coupled elasto-plastic-damage model for concrete was also successfully used in the calculations of concrete beams with basalt reinforcement. The research program included experimental and numerical analysis of the size effect in four-point bending beams. Numerical simulations were made by my friends from the department: MSc. Eng. M. Ostaszewska and Ph.D. Eng. E. Korol. Despite use of simplified calibration procedure, the satisfactory agreement was obtained with respect to force-displacement diagrams and crack pattern

Results of numerical simulations were published in the following journals from the JCR list: *Archives of Mechanics* (item 4.b.1), *Bulletin of the Polish Academy of Sciences-Technical Sciences* (item 4.b.2), *Computers and Concrete* (item 4.b.3 and 4.b.6), *European Journal of Environmental and Civil Engineering* (item 4.b.7), *Finite Elements in Analysis and Design* (item 4.b.9) as well as *Engineering Structures* (Korol E., Tejchman J., Mróz Z., 2017. Experimental and numerical assessment of size effect in geometrically similar slender concrete beams with basalt reinforcement. Eng. Struct., 141, 272-291). Obtained results and conclusions were also presented at international conferences: EURO-C 2010 (Appx. 5, item II.L.11), CMM 2011 (Appx. 5, item II.L.12), ECCOMAS 2012 (Appx. 5, item III.B.3), EURO-C 2018 (Appx. 5, item II.L.19).

B. *An improved elasto-visco-plastic model with non-local softening to describe concrete behaviour under dynamic loading*

As mentioned above, process of formation and propagation of cracks is one of the most fundamental concrete features. One of the factors that significantly influences development of cracks is velocity of applied load. Consequently, concrete is a highly rate-dependant material. Its mechanical properties, in particular the compressive and tensile strength, strongly depend on the strain rate. Two dynamic coefficients are introduced to describe growth of tensile *TDIF* (*tensile dynamic increase factor*) and compressive *CDIF* (*compressive dynamic increase factor*) strength. According to various research works for very high strain rates ($\dot{\varepsilon} \geq 100\ 1/s$), the increase of compressive strength can be over 2.5 times, and the increase of tensile strength even 10 times. In both cases, a strong exponential growth of strength is observed above a certain limit value of strain rates. The described dynamic effects are caused by various factors affecting the strength at various strain-rate levels. At relatively low velocities it is necessary to take into account the viscous effects associated with migration of water in the material pores. In turn at medium and high load velocities, the speed of cracks formation determines the increase of strength. Finally, at highest loading velocities the structural effect i.e. inertia forces have to be taken into account. The classical elasto-plastic constitutive laws (within continuum mechanics) do not allow to correctly reflect presented dynamic effects. It is necessary to modify them. In paper (item 4.b.2) I proposed a simple model for concrete under dynamic loading conditions. As a starting point I asumed the failure surface described with aid of Drucker-Prager (compression) and Rankine (tension) criteria. To introduce rate-dependency I enriched constitutive equations with an additional viscosity parameter via the Duvaut-Lions concept. In this approach partition of the total strain rate into an elastic strain rate and a visco-plastic strain rate was assumed. In addition, it is quite convenient to be implemented, since a visco-plastic solution is the update of an inviscid solution. The first resolution of elasto-plastic constitutive equations was carried out by considering the material as a rate-independent one, so the stress tensor and the hardening variable could be determined. In the second phase, the rate-dependency was incorporated. Thus, the updated visco-plastic stress and the updated visco-plastic rate parameter integrated over the time step are obtained. To obtain mesh insensitive FE-results also for low velocities I introduced the characteristic length into the model using again non-local regularization. I checked the effectiveness of the model with concrete samples subjected to uniaxial compression and tension. Dynamic FE simulations were performed for a wide range of loading velocities ($10^{-5} 1/s \leq \dot{\varepsilon} \leq 10^{2}\ 1/s$). The results were compared with experimental data and standard curves describing CDIF and TDIF coefficients. Obtained results showed that the elasto-visco-plastic formulation is able to properly reflect dynamic effects only for relatively high loading velocities ($\dot{\varepsilon} \geq 10^{-1}\ 1/s$). In turn, the calculated dynamic increase factors were insufficient at small and medium strain rates. In order to solve this drawback, in further works (items 4.b.4 and 4.b.5) I also proposed another way to modify the classical elasto-plastic formulation with non-local softening. I introduced the stress modification with function depending on the strain rate tensor. The idea is based on so-called theory of energy activation presented originally by Bažant. This modification significantly improved the efficiency of the model, in particular at small and medium strain rates. The numerically calculated CDIF and TDIF factors for uniaxial compression and tension test showed good agreement with experimental data. On the other hand, the results of 3D FE simulation for concrete beams under dynamic bending showed, for the highest loading velocities, a significant overestimation of the load-bearing capacity in comparison with the experiments. This effect was due to the so-called fragmentation phenomenon, which was not able to be properly reproduce within continuum mechanics model. Thus, to obtain more realistic results for highest loading velocities for concrete, I assumed a method of material stiffness reduction in finite elements (equivalent to a removal of finite elements) in order to simulate approximately progressive material fragmentation. The "removing" of finite elements leaded to improve the accordance of calculated load-bearing capacities in comparison with the experimental data.

Results of numerical calculations with concrete elements under dynamic loading conditions were published in following JCR journals: *Bulletin of the Polish Academy of Sciences-Technical Sciences* (item 4.b.2) and *Computers and Concrete* (item 4.b.5). In addition, results and conclusions were also presented at several international conferences: ECCOMAS 2012 (Appx. 5, item II.L.14), FraMCoS-8 2013 (Appx. 5, item II.L.16) and EURO-C 2014 (Appx .5, item II.L.18).

Summary

The presented results of numerous numerical FE simulations confirmed the ability of constitutive laws presented and implemented by my own to correctly reflect the behavior of real reinforced concrete and concrete members at complex stress states (mixed mode conditions). The proposed constitutive laws enriched with a characteristic length allowed also to obtain objective FE-results, i.e. independent of the finite element mesh.

The most important achievements resulted from the conducted research are as follows:

1) formulation and implementation (into the ABAQUS software) of an improved coupled elasto-plastic-damage model for concrete combining isotropic damage with elasto-plastic constitutive law and non-local softening to describe the behavior of concrete and reinforced concrete members under quasi-static (monotonic and cyclic) loading with taking in to account the strain localizations,

2) formulation/modification and implementation (into the ABAQUS software) of continuous constitutive laws with non-local softening to describe concrete behaviour under dynamic loading conditions (with taking in to account the strain localizations and fragmentation),

3) application of the above mentioned constitutive models in the large number of FE simulations for reinforced concrete and concrete members for a wide range of boundary and initial conditions as well as obtaining numerical results consistent with the experimental outcomes.

The presented material models for concrete can be successfully applied to:

1) FEM numerical calculations for various types of reinforced concrete members, for which it is important to accurately reflect the actual failure mechanism in complex stress states,
2) FEM numerical calculations for various concrete elements subjected to cyclic and dynamic loads,
3) simulating formation and evolution of the strain localization in reinforced concrete elements and analysis of influence of the particular geometrical and material parameters on behavior of these members.

It should be also noted that applied modifications of the ABAQUS software, in particular with the implementation of non-local algorithms, go far beyond the standard extensions used in ABAQUS subroutines, such as defining user finite elements or user material law definition.

5. Description of other academic and research achievements

<u>Before obtaining PhD degree</u>

I owe my contact with scientific activity to Prof. Ph.D., D. Sc., Eng. Jacek Tejchman from the Gdańsk University of Technology who was the supervisor of my master's thesis. After graduating (October 2003), I became a participant in the PhD Studies at the Faculty of Civil and Environmental Engineering at GUT. My promoter/supervisor was again prof. J. Tejchman, with whom I started scientific and professional cooperation, which has continued until today (from 2004 as a research assistant and then assistant professor in the department headed by prof. J. Tejchman).

From the very beginning, my research focused on modeling the behavior of concrete and reinforced concrete elements using constitutive laws within continuum mechanics. These laws usually require defining the softening and it is therefore necessary to use the regularization method to obtain FE-results insensitive on finite element mesh size. The major regularization technique in my case was the non-local (integral type) approach. The use of this method was initiated in our department by Ph.D., D. Sc., Eng. J. Bobiński. Collaboration with him introduced me the issues of implementing non-local models, and also accelerated work on creating my own non-local procedures and algorithms within ABAQUS software. I have used this software from the very beginning as a fundament for all my computational algorithms as well as a preprocessor, postprocessor and global solver in FEM simulations.

The title of my dissertation was: "Application of elasto-plastic model with stiffness degradation and non-local softening to describe behaviour of concrete members under cyclic loading". I have defended my Ph.D. thesis on 09.03.2009. The main purpose of the work was application of different types of elasto-plastic coupled models with stiffness degradation and enriched with the characteristic length of microstructure for numerical modeling of concrete members under cyclic loading.

Detailed goals (achievements) can be defined as:
- verification of the correctness and efficiency of the non-local elasto-plastic model and the non-local isotropic damage model in the field of numerical modeling of reinforced concrete elements,
- implementation into the commercial ABAQUS/Standard software of various concepts of coupled constitutive laws available in the literature along with their enrichment by non-local integral-type regularization,
- parametric studies of the implemented models and determination of the influence of individual parameters on obtained FE-results, in particular with respect to the shape of the load-displacement curve in the softening regime as well as the characteristic shape and size of the localized zones.

Within my dissertation I reviewed existing constitutive models for concrete. I described the problem of regularization and non-local theory and its thermodynamic basis. I presented detailed algorithms of non-local models: an elasto-plastic, isotropic damage (continuum damage mechanics), coupled and damage in the form of elasto-plastic law. The models were then verified with static tests available in the literature: uniaxial tension (dog-bone specimens), uniaxial compression, three-point bending (beams with notch) and four-point bending (beams with notch). In turn, the coupled models were verified using: three-point and four-point cyclic bending tests (beams with notch). The last aspect of my Ph.D. thesis were numerical simulations of reinforced concrete members. The calculations were performed with a non-local elasto-plastic model and a non-local isotropic damage model. FE simulations were made for three types of reinforced concrete beams with scaled height and length and various reinforcement ratios (Walraven (1978)).

A series of simulations were performed in which the influence of many parameters was analyzed. The effect of fracture energy, characteristic length, tensile strength, reinforcement ratio as well as the bond-slip law between steel and concrete were investigated. The bearing capacity of the beams as well as the shape, spacing and width of the localized zones were analyzed.

Results of research works with respect to above issues were published in journals from the JCR list: *Mechanics Research Communications* (Appx. 5, item II.A.1) and *Computers and Concrete* (Appx. 5, item II.A.2). Obtained results and conclusions were also presented at international conferences: WCCM 2006 (Appx. 5, item III.B.1), CMM 2005 (Appx. 5, item II.L.1), CFRAC 2007 (Appx. 5, item II.L.3), CMM 2007 (Appx. 5, item II.L.4), ECCOMAS 2008 (Appx. 5, item II.L.7) and domestic: SolMech 2006 (Appx. 5, item II.L.2), AMCM 2008 (Appx. 5, item II.L.6) and SolMech 2008 (Appx. 5, item III.B.2).

<u>After obtaining PhD degree</u>

In addition to the achievements described in paragraph 4.c, my remaining scientific and research accomplishments after obtaining the PhD degree focused on two areas:

A) fatigue testing of concrete and reinforced elements with steel and basalt reinforcement,

B) numerical analysis of the size effect in concrete beams

A. *Fatigue testing of concrete and reinforced elements with steel and basalt reinforcement*

As a part of the Project "Innovative resources and effective methods of safety improvement and durability of buildings and transport infrastructure in the sustainable development" (Appx. 5, item II.J.) I planned and carried out a research program concerning fatigue life tests of concrete elements with non-steel reinforcement. The main purpose of the research work was to determine the suitability of the using of reinforced concrete members with reinforcement in the form of basalt bars in the context of fatigue life of such elements. The experimental program included fatigue tests of concrete beams and reinforced concrete beams subjected to three-point cyclic bending. In total, I examined over 110 beams. In the first stage, fatigue tests were carried out for concrete beams with notch. I made two series of tests for beams made of concrete with different grain size. Two types of concrete mix were used. The round-shape sand and gravel particles were used with a fine fraction (d_{max} = 2 mm, d_{50} = 0.5mm) and with standard fraction (d_{max} = 16 mm, d_{50} = 2 mm). Each series consisted of 15 beams. The tests were carried out with frequency of 2 Hz, the stress level was from S = 0.65 up to S = 0.95, and the obtained fatigue life ranged from N = 12 to N = 2,000,000 cycles. During the experiments, the number of cycles as well as the increase in displacements associated with the subsequent load cycles were recorded. In order to record the initiation and development of the localized zones I used the digital image correlation (DIC) technique. Thanks to this, I obtained images of strain localization zones preceding the appearance of macro-cracks. The information collected at this stage of work was the starting point for main experimental research program for reinforced concrete members. In addition, obtained results formed the basis for calibration of the numerical model. In the second stage, I performed tests for reinforced concrete beams. The experimental program included a total of four series (80 beams). Beams with reinforcement made of steel bars and with reinforcement made of basalt bars were tested. As in the first step, two different types of concrete mix were used. In both cases, the high reinforcement ratio was applied to guarantee desirable failure mechanism (concrete shear). The beams were loaded with frequency of 2 Hz, the stress level was again from S = 0.65 up to S = 0.95, and the obtained fatigue life ranged from N = 20 to N = 4,000,000 cycles. The number of cycles and displacement were recorded in all tests. On the basis of the results of fatigue test, the S-N relationships (so-called fatigue curves) were obtained for all types of tested beams. Analysis of S-N curves allowed to formulate conclusions regarding the appropriateness of using the basalt reinforcement. Beams with basalt reinforcement showed only a little worse durability in comparison with compared elements with standard reinforcement. Interestingly, elements with basalt reinforcement were characterized in this aspect by better efficiency compared to reinforcement based on glass, aramid or carbon fibers. The major problem in the replacement use of basalt bars is a different characteristic of the work of such reinforced structural members. Due to clearly lower modulus of elasticity, concrete elements reinforced with basalt bars show much larger deformations (deflections and crack widths).

Simultaneously to experimental research, I worked on creating a numerical model for concrete under fatigue loading. As a starting point, I assumed the standard continuum damage model proposed originally by Mai et al. (Mai S.H., Le-Corre F., Foret G., Nedjar

B., 2012. A continuum damage modeling of quasi-static fatigue strength of plain concrete. International Journal of Fatigue 37, 79-85), which assumes that the failure surface is described by a function dependent upon the damage parameter. For fatigue loads, we observe the increase of degradation despite loading the element below its load-bearing capacity. To solve this problem, it is necessary to introduce modifications to the standard formulation and assume alternative damage activation criterion. In the model, I adopted the extension originally proposed by Marigo, (Marigo J.J. 1985. Modelling of brittle and fatigue damage for elastic material by growth of microvoids. Eng. Fract. Mech. 21(4), 861-74) consisting in introduction of an additional power function in damage definition. In addition, I introduced also a characteristic length using a non-local approach. The model was initially positively verified based on the results of fatigue tests for concrete beams with notch.

The last aspect of fatigue research concerned the use of advanced X-ray micro-computed tomography system to analyze the process of fracture evolution in concrete elements under fatigue loading. I proposed the concept of assessment the damage growth in a concrete specimen during a fatigue test using X-ray micro-computed tomography. In the tests concrete samples under uniaxial cyclic load were used. The research methodology consisted in scanning the structure of the sample at subsequent stages of the test (10,000, 30,000, 60,000 and 70,000 cycles). A very accurate image of the microstructure of the sample was obtained due to use of high-resolution X-ray scanning. The applied technique allowed not only for qualitative but also for quantitative assessment of damage development in subsequent test phases. On the basis of the quantitative analysis of the number of open and closed pores, the percentage increase in the volume of cracks in the concrete sample was estimated. The obtained results indicate a strong non-linear increase of damage in the final phase of the test, preceding the fatigue strength limit.

The results and conclusions from fatigue experiments were included in the report summarizing grant. Partial research results were presented at conferences organized as part of the grant (Appx. 5, item II.L.13, II.L.15 and II.L.17) and at two international conferences: FraMCoS-8 2013 (Appx. 5, item II.L.16) and EURO-C 2014 (Appx. 5, item II.L.18). Part of the research results was also published in the journal from the JCR list: *International Journal of Fatigue* (Appx. 5, item II.A.3).

B. Numerical analysis of the size effect in concrete beams

Based on my previous experience, the introduction of a characteristic length and proper regularization of constitutive law allows to correctly reflect of the scale effects in concrete and reinforced concrete elements. However, there are several factors influencing the accuracy of this projection. The aim of my research in this aspect was analysis of influence of the fracture energy (and the type of assumed curve in softening regime) and taking into account the effect of the so-called boundary layer (area at the outer edges of elements with changed material parameters). I also analyzed the influence of applied method of non-local averaging on result within elasto-plastic formulation. Numerical simulations were carried out for a series of geometrically similar concrete beams with and without notch subjected to three-point bending. As the reference data, I used the results of experimental studies presented by Hoover and others (Hoover C.G., Bažant Z.P., Vorel J., Wendner R., Hubler M.H., 2013. Comprehensive concrete fracture tests: Description and results. Eng. Fract. Mech. 114, 92-103). They examined beams of various sizes (four types) and different sizes of notch (five sizes). In total I made numerical simulations for 18 types of beams. Two approaches were used to describe cracks in concrete. First, eXtended Finite Element Method (XFEM) describing cracks as discrete cohesive ones with bilinear softening was chosen. In addition, I also used the exponential softening function and the modification of the bilinear function using the Bézier curve. Alternatively, an elasto-plastic constitutive law with Rankine criterion, associated flow rule, bilinear softening and with standard or modified non-local averaging was used. The results of numerical simulations showed that the use of the elasto-plastic model generally led to overestimation of the load-bearing capacities. The use of a modified non-local averaging method only slightly improved obtained results. Thus, further research is needed in order to improve compliance. On the other hand, the results obtained within XFEM approach were characterized by very good accordance with the experiments. In addition, the boundary layer had a pronounced influence on error reductions in calculated ultimate stresses. The results of so far work in this area have been published in the journal from the JCR list: *Polish Maritime Research* (Appx. 5, item II.A.4) and in the peer-reviewed publication *MATEC Web of Conferences* (Appx 5, item II.E.5). The results were also presented at the 64 Scientific Conference of the Committee for Civil Engineering of the Polish Academy of Sciences and the Science Committee of the Polish Association of Civil Engineers (Appx. 5, item III.B.4).

In total, I co-authored 11 papers in JCR journals: *Archives of Mechanics* (1), *Bulletin of the Polish Academy of Sciences-Technical Sciences* (1), *Computers and Concrete* (4), *European Journal of Environmental and Civil Engineering* (1), *Mechanics Research Communications* (1), *Finite Elements in Analysis and Design* (1), *International Journal of Fatigue* (1) and *Polish Maritime Research* (1).

The total impact factor (IF) according to the Journal Citation Reports (JCR) according to the year of publication for all presented publications (paragraphs 4 and 5) is **13,523** and the summary number of points (according to the list of Ministry of Science and Higher Education from 26.01.2017) is **330**.

The experience resulting from my research work on advanced FEM modeling I additionally used in my engineering practice. Simultaneously with my scientific activity, I carry out expert and project activities in the field of construction and engineering. I am the author or co-author of a number of structural design works (Appx. 5, item II.B) as well as expert opinions and technical reports (Appx. 5, item III.M).

6. Didactic activities

Since the start of my employment at Gdansk University of Technology (November 2004) I have classes on full-time studies in Civil Engineering (in the past also in Environmental Engineering). Currently I have classes from the following subjects (Appx. 5, item III.J):

1. Industrial Construction I (undergraduate studies) – lectures (in past also tutorials and projects),
2. Building Construction I (undergraduate studies) – tutorials and projects,
3. Building Construction II (undergraduate studies) – tutorials and projects,
4. Design of Complex Engineering Structures (graduate studies) – lectures, tutorials and projects,
5. Complex Concrete Structures (graduate studies) – tutorials and projects (classes conducted in English).

I co-prepared the program of the following subjects: Design of Complex Engineering Structures and Industrial Construction I. In the past I had project classes from Wooden Structures and classes from Building Construction in Environmental Engineering studies.

Since the year 2009 I have been the supervisor of 40 and the reviewer of 53 bachelor thesis and I have been the supervisor of 22 and the reviewer of 37 master thesis on full-time and part-time studies (Appx. 5, item III.J).

I was the co-author of the auxiliary materials for the subject Building Construction I and Industrial Construction I (project) which complement the program content of this subjects.

7. Organisation activities, scientific cooperation and popularization of science

I am actively involved in the several tasks in my Department. I am the person responsible for measure and research equipment in the field of cyclic and fatigue tests within Department Laboratory. I am also one of the administrators of computing servers owned by our Department.

I am an active participant of scientific conferences (Appx. 5, item II.L and III.B). I took part in 11 national conferences and 10 international conferences; I had (in total) 19 oral presentations. The most important cyclic conferences I attend are: Computational Modelling of Concrete Structures EURO-C (2010, 2014, 2018), Conference on Computer Methods in Mechanics CMM (2005, 2007, 2009, 2011). I was also a participant of the other cyclic conferences, among others: Solid Mechanics Conference SolMech (2006, 2008) and European Congress on Computational Methods in Applied Sciences and Engineering ECCOMAS (2008, 2012)

I took part in the course on modelling localisations of deformations run by Prof. M. Jirásek at Czech Technical University in Prague (Appx. 5, item III.L.1).

In the years 2016-2018 I took an active part in the Baltic Science Festival. As part of this event, I prepared lectures and thematic classes.

I have also prepared reviews for papers submitted to international journals, e.g.: "Structures" - Research Journal of the Institution of Structural Engineers (Appx. 5, item III.P).