Załącznik 4 / Appendix 4

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

Contents:

1. Name and surname

Łukasz Skarżyński

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. PhD Degree in Technical Science, discipline: Civil Engineering. Faculty of Civil and Environmental Engineering, Gdańsk University of Technology. Dissertation's title: Macroscopic and mesoscopic modelling of strain localization in concrete. Supervisor: prof. dr hab. inż. Jacek Tejchman. Reviewers: dr hab. inż. Jerzy Pamin, prof. PK. and dr hab. inż. Jarosław Górski, 2011.
2. Bachelor of Science, Faculty of Civil and Environmental Engineering, Department of Highway Engineering, Gdańsk University of Technology, 2006.
3. Master of Science, Faculty of Civil and Environmental Engineering, Department of Mechanics and Bridges, Gdańsk University of Technology, 2006.

3. Information about employment in academic/research institutions

1. From 2011: Adjunct. Faculty of Civil and Environmental Engineering, Gdańsk University of Technology.
2. 2006-2011: Assistant. Faculty of Civil and Environmental Engineering, Gdańsk University of Technology.

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

Experimental investigations and numerical simulations of fracture in concrete and reinforced concrete.

b. Publications included in the scientific achievement

1. **Skarżyński Ł.**, Tejchman J., 2012. Numerical mesoscopic analysis of fracture of fine-grained concrete under tensile loading. *Archives of Civil Engineering*, LVIII, 3, 331-361.
2. **Skarżyński Ł.**, Tejchman J., 2013. Modelling the effect of material composition on the tensile properties of concrete. *Understanding tensile properties of concrete. Book series: Woodhead Publishing Series in Civil and Structural Engineering*, 48, 52-97.
3. **Skarżyński Ł.**, Kozicki J., Tejchman J., 2013. Application of DIC technique to concrete – study on objectivity of measured surface displacements. *Experimental Mechanics*, 53(9), 52-97.
4. **Skarżyński Ł.**, Tejchman J., 2013. Experimental investigations of fracture process using DIC in plain and reinforced concrete beams under bending. *Strain*, 49(6), 521-543.

5. **Skarżyński Ł.**, Nitka M., Tejchman J., 2014. Two-scale model for concrete beams subjected to three point bending – numerical analyses and experiments. *Computational Modelling of Concrete Structures, Proceedings of the EURO-C 2014 Conference*, March 24-27, St. Anton am Arlberg, Austria, vol.1, 149-158.
6. Nitka M., **Skarżyński Ł.**, Tejchman J., 2015. Simulations of fracture in concrete beams under bending using a continuum and discrete approach. *XIII International Conference on Computational Plasticity: Fundamentals and Applications COMPLAS 2015,* September 1-3, Barcelona, Spain, 1065-1076.
7. **Skarżyński Ł.**, Nitka M., Tejchman J., 2015. Modelling of concrete fracture at aggregate level using FEM and DEM based on X-ray micro-CT images of internal structure. *Engineering Fracture Mechanics*, 147, 13-35.
8. **Skarżyński Ł.**, Tejchman J., 2016. Experimental investigations of fracture process in concrete by means of X-ray micro-computed tomography. *Strain*, 52(1), 26-45.
9. **Skarżyński Ł.**, Marzec I., Tejchman J., 2017. Experiments and numerical analyses for composite RC-EPS slabs. *Computers and Concrete*, 20(6), 689-704.
10. **Skarżyński Ł.**, Marzec I., Drąg K., Tejchman J., 2018. Numerical analyses of novel prefabricated structural wall panels in residential buildings based on laboratory tests in scale 1:1. *European Journal of Environmental and Civil Engineering*, doi: 10.1080/19648189.2018.1474382.
11. **Skarżyński Ł.**, Suchorzewski J., 2018. Mechanical and fracture properties of concrete reinforced with recycled and industrial steel fibers using Digital Image Correlation technique and X-ray micro computed tomography. *Construction and Building Materials*, 183, 283-299.
12. **Skarżyński Ł.**, Marzec I., Tejchman J., 2019. Fracture evolution in concrete compressive fatigue experiments based on X-ray micro-CT images. *International Journal of Fatigue*, 122, 256-272.

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

Fracture including strain localization zones and macro-cracks is a fundamental phenomenon in quasi-brittle materials. It is a major reason of damage in concrete under mechanical loading contributing to significant degradation of material strength. Fracture is always preceded by the occurrence of narrow localized zones of intense deformation (called fracture process zones (FPZ)) that have a certain volume being not negligible as compared to the specimen size. With an increase of deformation, macro-crack arises. The subject of my scientific interests is fracture in plain concrete and reinforced concrete with bars or fibers. During my research, I concentrated on both experimental investigations and numerical simulations of a fracture process in concrete. In static (monotonic and fatigue) experiments, I used the most advanced measuring techniques: a) non-invasive digital image correlation (DIC) technique for displacement measurements on the concrete surface and b) X-ray micro-computed tomography system (micro-CT) for a 3D visualization of concrete meso-structure. To identify porous interfacial zones between the aggregate and cement matrix (interfacial transition zones (ITZs)), a scanning electron microscope (SEM) was used. Based on monotonic experimental outcomes, I carried out comprehensive numerical simulations by the finite element method (FEM) at the aggregate level (called the meso-level). Concrete was described as a four-phase material composed of aggregate, cement matrix, ITZs and macro-pores. Mesoscopic computations were performed with an isotropic damage model. In order to properly describe strain localization (width, inclination and spacing), the constitutive model was enhanced in the softening regime by a characteristic length of micro-structure with the aid of a non-local theory. The characteristic length was determined with measurements by DIC. The obtained results were directly compared with the own laboratory tests. In addition, my research works concerned comprehensive macroscopic numerical simulations of material strength and fracture pattern in large reinforced concrete elements of the energy-saving residential building. The elasto-plastic model with the Drucker-Prager criterion defined in compression and with the Rankine criterion defined in tension enhanced by a characteristic length of micro-structure and bond-slip law between concrete and reinforcement was used. The 2D and 3D computations of reinforced concrete elements were performed.

My research activities can be divided into following main three topics:

A. Experimental investigations of fracture evolution in concrete.
B. Mesoscopic numerical simulations of concrete with real internal structure.
C. Macroscopic numerical simulations of large reinforced concrete elements of energy-saving residential building.

A. Experimental investigations of fracture evolution in concrete

Experimental tests were conducted for elements under monotonic bending and splitting as well as under fatigue compression. Plain concrete and concrete reinforced with bars or dispersed reinforcement in the form of industrial and recycled steel fibers obtained from used car tires were applied.

Comprehensive numerical calculations of strain localization (formation and evolution, shape and width) and a macro-crack formation were initially carried out using a non-invasive digital image correlation (DIC) technique that enabled to determine a characteristic length of micro-structure (an important parameter in non-local constitutive models) and capture an instant of the formation of a macro-crack (important information for coupled continuous-discontinuous constitutive models for concrete). The DIC technique measures displacements on the surface of concrete elements by a successive post-processing of digital images taken with a constant time between frames from a professional digital camera. A deformation pattern is detected by comparing two consecutive images captured by a camera which remains in a fixed position with its axis oriented perpendicularly to the plane of deformation. To better correlate the images, a special tracer is applied on the concrete surface. To find a local displacements between two images, a search patch, which moves around the compared images with certain step, is extracted. Three functions are of a major importance for DIC: image field intensity, cross-correlation function and interpolation function. Furthermore, on the basis of experiments with concrete beams subjected to three-point bending I carried out detailed studies on the accuracy and objectivity of DIC in reference to measured displacements with respect to a search patch size, distance between search patch centers and image length resolution (in pixel per millimeter). In order to determine the width of a localized zone, the measured displacements from DIC were fitted by the error function ERF whereas the surface strain profiles calculated from the displacement profiles were fitted by the normal distribution (Gauss) function. The measured surface displacements due to their small magnitude were very sensitive to the image length resolution - the higher image length resolution, the smaller the surface displacements. Based on experimental tests, an original method was developed to determine the width of localized zones. Moreover, I carried out comprehensive experimental tests on concrete beams subjected to three-point bending.

Concrete was prepared from 8 different mixes. During the experiments, the influence of the shape, size and volume of aggregate on the evolution, shape and width of strain localization zone was carefully investigated. Stain localization zones were non-symmetric and strongly curved due to the presence of stochastically distributed aggregate grains. The zone tortuosity increased with increasing volume and roughness of aggregate. The crack branches also happened, in particular, in concrete with low volume of aggregate and rounded-shape particles. Localized zones were always created before the peak on the vertical force-CMOD diagram at 80-90% of the maximum vertical force. The maximum width of the localized zone (just before the formation of a macro-crack) was 2,5-3,5 mm. The width of the localized zone strongly grew width increasing maximum aggregate size and slightly grew with diminishing aggregate volume. The length and height of the localized zone above the notch were practically not affected by a concrete mix. The beam strength increased strongly with increasing aggregate size and moderately with increasing volume of aggregate and aggregate roughness. A macro-crack occurred in a softening regime for CMOD about two times larger than this at the peak force.

The results were presented in 2 journals from the JCR list: *Experimental Mechanics* (item 4.b.3) and *Strain* (item 4.b.4):

[1] Skarżyński Ł., Kozicki J., Tejchman J., 2013. Application of DIC technique to concrete – study on objectivity of measured surface displacements. *Experimental Mechanics*, 53(9), 52-97.
[2] Skarżyński Ł., Tejchman J., 2013. Experimental investigations of fracture process using DIC in plain and reinforced concrete beams under bending. *Strain*, 49(6), 521-543.

They were also presented in the form of the oral presentations at international conferences: *ECCOMAS* in Vienna in 2012 (Appendix 5, item II.L.9), *ICEM* in Cambridge in 2013 (Appendix5, item II.L.12), *FramCos* in Toledo in 2013 (Appendix 5, item III.B.3) and *EURO-C* in St. Anton am Arlberg in 2014 (Appendix 5, item III.B.4).

The second topic of my scientific interests was the X-ray micro-computed tomography (micro-CT). It is the most advanced non-invasive research method that allows for visualizing the internal structure of investigated specimens based on two-dimensional projections taken at different angles. The micro-CT is constructed of an X-ray tube with a small size of the spot, the appropriate energy and geometry of the radiation beam and a detector based on a CDD matrix converting the photons of radiation into electrical impulses. It is based on the same assumptions as the classical computed tomography but due to the use of a smaller spot of radiation, it is possible to obtain a higher resolution of the reconstructed image. A micro-tomography device has a resolution of about 1 micrometer. The resolution of measurement depends on 4 main factors: spot size, lamp-specimen distance and specimen-detector distance (determined by the size of the specimen), detector resolution and reconstruction process. Reconstruction is the process of the visualization of the specimen interior as a superposition of registered two-dimensional projections. In micro-tomographic measurements, in contrast to the medical tomography, the geometry of the rotating specimen is used, the position of the lamp and detector is constant and during the measurements, the specimen is rotating by a specific angle. In years 2013 and 2014, I designed and built the most advanced station for non-invasive visualization of material micro-structures together with a module for testing the surface microstructure of materials using the scanning electron microscope (SEM). It is worldwide unique station composed of 2 micro-tomography systems where one of them is a prototype: X ray micro-CT Skyscan 1173 integrated with the quasi-static loading machine

Instron that allows for continuous investigations and analyses of microstructural phenomena during a deformation process. First, the micro-CT experiments were carried out on concrete beams subjected to three-point bending. After failure, a concrete cuboid with the dimensions 40×40×80 mm was cut out in a cracked area (the notch region). The X-ray micro-CT system proved to be a powerful tool for the visualization of concrete micro-structure and crack propagation in concrete. It allows to easily distinguish different material phases (aggregate, cement matrix and macro-pores). Due to the too low resolution of micro-CT images, the porous ITZ zones, where a fracture process is initiated, could not be detected. To measure the width of ITZs, the scanning electron microscope with the magnification factor of 30000 was used. The width of the ITZs along the aggregate particles changed between 30 μm do 50 μm. The crack mainly propagated through ITZs that surrounded aggregate grains and rarely through large macro-pores, however, it sometimes propagated through weak aggregate particles. The crack in 3D was visualized for which the width, height and volume were calculated. The total volume of crack was 0,8% of the total specimen volume. Next, micro-CT and SEM images were used as a basis for mesoscopic numerical simulations by FEM where concrete was described as a four-phase material composed of aggregate, cement matrix, ITZs and macro-pores. Furthermore, I analyzed a fracture process in concrete reinforced with industrial steel fibers and recycled steel fiber obtained from used car tires. I identified and characterized open and closed air pores in cubic concrete specimens with the dimensions of 75×75×75 mm. The X-ray micro-computed tomography system was also used to visualize and characterize steel fibers embedded in concrete specimens in terms of the diameter, length and orientation. The measured diameter of recycled steel fibers varied between 0,15 mm and 0,33 mm and the length varied mainly between 5 mm and 40 mm. The deviation of fibers from the vertical axis was from 0^0 to 30^0 for 8% of fibers, from 30^0 to 60^0 for 30% of fibers and from 60^0 to 90^0 for 62% of fibers. In addition to the quantitative measurements of pores and fibers, I presented their visualization in 3D. Moreover, the evolution of a fracture process was studied using the X ray micro-CT Skyscan 1173 integrated with the quasi-static loading machine Instron 5569 that allowed for continuous observation of micro-structural phenomena without a specimen unloading. Experimental tests were carried out on notched cubic specimens (initial notch height 10 mm and width 5 mm) subjected to wedge splitting (WST). The quasi-static tests were performed with a controlled displacement rate. The crack mouth opening displacement (CMOD) gauge was placed in the notch. On the basis of X-ray micro-CT images, a 3D macro-crack was shown for various loading stages. The crack volume in tested specimens varied between 1,8% and 2,0% - it means that both types of fibers had a similar ability of crack-bridging. The latest research works concerned the cubic concrete specimens with the dimensions of 40×40×40 mm subjected to cycling compression with the frequency of 2 Hz. The main goal of experiments was to determine the evolution of a damage factor with increasing fatigue loading cycles. The scans were made after 10000, 30000, 60000 and 70000 loading cycles (fatigue life of the specimen was 73217 cycles). The increase of the damage factor was of a hyperbolic shape and three different damage parts might be distinguished: a micro-crack part, a transitory part where micro-cracks coalesced to form a macro-crack and a macro-crack extension part. The maximum volume of cracks, close to the failure, was 5,6% and the maximum crack width was 0,72 mm.

The results were discussed in 4 journals from the JCR list: *Engineering Fracture Mechanics* (item 4.b.7), *Strain* (item 4.b.8), *Construction and Building Materials* (item 4.b.11) and *International Journal of Fatigue* (item 4.b.12):

[1] Skarżyński Ł., Nitka M., Tejchman J., 2015. Modelling of concrete fracture at aggregate level using FEM and DEM based on X-ray micro-CT images of internal structure. *Engineering Fracture Mechanics*, 147, 13-35.
[2] Skarżyński Ł., Tejchman J., 2016. Experimental investigations of fracture process in concrete by means of X-ray micro-computed tomography. *Strain*, 52(1), 26-45.
[3] Skarżyński Ł., Suchorzewski J., 2018. Mechanical and fracture properties of concrete reinforced with recycled and industrial steel fibers using Digital Image Correlation technique and X-ray micro computed tomography. *Construction and Building Materials*, 183, 283-299.
[4] Skarżyński Ł., Marzec I., Tejchman J., 2019. Fracture evolution in concrete compressive fatigue experiments based on X-ray micro-CT images. *International Journal of Fatigue*, doi.org/10.1016/j.ijfatigue.2019.02.002.

and in the conference materials from Web of Science (items 4.b. 5 and 4.b.6). They were also the content of oral presentations at international conferences: *EURO-C* in St. Anton am Arlberg in 2014 (Appendix 5, item III.B.4), *CFRAC* in Cachan in 2015 (Appendix 5, item III.B.5) and *COMPLAS* in Barcelona in 2015 (Appendix.5, item III.B.6).

B. Mesoscopic numerical simulations of concrete with real internal structure

In order to realistically model strain localization zones in concrete, it is necessary to take its microstructure into account that strongly affects its global response. In my thesis, to investigate strain localization, I chose a mesoscopic isotropic damage three-phase model enhanced by a characteristic length of microstructure by means of non-local softening. Concrete was described at the aggregate level as a material composed of aggregate, cement matrix and ITZs. I took into account the beams of a different height and various shape, size, volume and stiffness of aggregate. Next, the three-phase model was enhanced by the presence of macro-pores to create a four-phase concrete model. The main novelty of my work with a four-phase concrete model concerned the implementation of real material microstructure, based on 3D images obtained from micro-CT. It enabled to directly compare numerical simulations by FEM with experimental results. The characteristic length of microstructure was determined to be equal to l_c=1,5 mm for which the computed material strength, shape and geometry of localized zones showed the best agreement with the experimental results. The width of the localized zone above the notch was about (2-4)×l_c. It increased with decreasing volume of aggregate from 2×l_c (for aggregate volume 60%) to 4×l_c (for aggregate volume 30%). It increases also with increasing characteristic length. It was not affected by the aggregate size, aggregate shape and beam height. The material's strength increased with increasing characteristic length, aggregate volume and aggregate shape and decreasing beam height. It also depended on the aggregate distribution. The material softening was strongly influenced by a characteristic length, volume and shape of aggregate and beam height. The computations revealed a very important role of ITZs between the aggregate and cement matrix. Their width and stiffness had a huge impact on the material strength and shape of localized zones.

The results were published in 2 journals from the JCR list: *Engineering Fracture Mechanics* (item 4.b.7) and *Strain* (item 4.b.8):

[1] Skarżyński Ł., Nitka M., Tejchman J., 2015. Modelling of concrete fracture at aggregate level using FEM and DEM based on X-ray micro-CT images of internal structure. *Engineering Fracture Mechanics*, 147, 13-35.

[2] Skarżyński Ł., Tejchman J., 2016. Experimental investigations of fracture process in concrete by means of X-ray micro-computed tomography. *Strain*, 52(1), 521-543

and in the conference materials from Web of Science (items 4.b.5 and 4.b.6), in peer-reviewed journal: *Archives of Civil Engineering* (item 4.b.1) in a book chapter *Woodhead Publishing Series in Civil and Structural Engineering* (item 4.b.2). They were also presented as the oral presentations at some international conferences: *ECCOMAS* in Vienna in 2012 (Appendix 5, item II.L.9), *ICEM* in Cambridge in 2013 (Appendix 5, item II.L.12), *FramCos* in Toledo in 2013 (Appendix 5, item III.B.3), *CFRAC* in Cachan in 2015 (Appendix 5, item III.B.5), *COMPLAS* in Barcelona in 2015 (Appendix 5, item III.B.6) and *Bruker Micro-CT User Meeting* in Bruges (2015), Luxembourg (2016), Brussels (2017) and Ghent (2018) (Appendix 5, items II.L.13-16).

C. Macroscopic numerical simulations of large reinforced concrete elements of energy-saving residential building

Within this part of my scientific activity, I was involved in the optimization of large innovative prefabricated reinforced concrete elements of energy-saving residential buildings. First, the slabs with the dimensions of 7,07×2,40×0,3 m, composed of RC ribbed box elements with the core from a EPS foam as a thermal insulation were investigated. The slabs were subjected to four-point bending and the quasi-static tests were performed with controlled displacement rate. The experimental slab failure was brittle and characterized by the occurrence of a diagonal shear crack. The mean experimental spacing of main vertical cracks was smaller than calculated by analytical formulae. The experiments were numerically evaluated using FEM based on a continuum macroscopic model for concrete. The elasto-plastic model with the Drucker-Prager criterion defined in compression and with the Rankine criterion defined in tension was used. In order to describe strain localization in concrete, the model was enhanced in the softening regime by a characteristic length of micro-structure by means of a non-local theory. In addition, a bond-slip law between concrete and reinforcement was also considered. The good accordance between the numerical and experimental outcomes was achieved with respect to the failure mode, shear strength, deflection and location of the critical diagonal localization shear zone. The experimental shear strength was realistically described with the analytical formulae, however, the inclination of the critical diagonal shear crack to the horizontal was significantly higher in experiments than in a theoretical solution. Next, the experimental and numerical investigations on prefabricated composite building wall panels with the dimensions of 6,60×3,00×0,3 m for energy-saving residential building were performed. The wall panels in the full-scale 1:1 were analyzed in three different variants: a) slab without holes loaded by a single concentrated force – failed by rapture of lower reinforcement, b) slab without holes loaded by three concentrated forces – failed in a rapid brittle way due to local damage of concrete and c) slab with window and door holes loaded by three concentrated forces – failed rapidly due to the reinforcement rupture in the frame beam. During the experiments, the comprehensive measurements of the wall panel deflection, spacing and width of cracks, stress in concrete and reinforcement were conducted. The experiments were numerically evaluated using FEM based on constitutive continuum macroscopic model for concrete. Once more, the enhanced elasto-plastic model with Drucker-Prager criterion defined in compression and with the Rankine criterion defined in tension was used. In computations, the influence of the fracture energy, bond stiffness, characteristic length and size of the finite element was investigated. The numerical outcomes were similar as the experimental results with respect to the maximum vertical force, shape of the force-deflection curve, failure mode, geometry of localization zones and normal stresses in tensile reinforcement and compressive concrete. The calculated vertical force always increased with increasing tensile and compressive fracture energy and bond stiffness. The tensile fracture energy strongly affected the moment of re-hardening on the force-deflection curve.

The results were published in 2 journals from the JCR list: *Computers and Concrete* (item 4.b.9) and *European Journal of Environmental and Civil Engineering* (item 4.b.10):

[1] Skarżyński Ł., Marzec I., Tejchman J., 2017. Experiments and numerical analyses for composite RC-EPS slabs. *Computers and Concrete*, 20(6), 689-704.
[2] Skarżyński Ł., Marzec I., Drąg K., Tejchman J., 2018. Numerical analyses of novel prefabricated structural wall panels in residential buildings based on laboratory tests in scale 1:1. *European Journal of Environmental and Civil Engineering*, doi: 10.1080/19648189.2018.1474382.

Summary

The applied, very advanced research methods, allowed for better recognition of a fracture process in concrete and reinforced concrete elements. The unique station where a micro-computed tomography system was integrated with a quasi-static loading machine allowed for investigations of fracture at the aggregate level during a continuous deformation process. The numerical simulations performed by FEM showed the ability of a four-phase model to realistically describe the concrete behaviour under loading. The experiments and numerical simulations were carried out for various boundary conditions.

The most important achievements of my experimental investigations and numerical simulations by FEM include:

1. Description of a fracture process in concrete and reinforced concrete elements (strain localization zones and discrete macro-cracks) for various boundary conditions using advanced non-invasive methods: DIC, micro-CT and SEM.
2. Implementation of a four-phase concrete model with a real meso-structure by taking into account the presence of aggregate, cement matrix, ITZs and macro-pores based on 3D micro-CT images.
3. Design and construction of a unique station based on a micro-computed tomography system integrated with a quasi-static loading machine for a non-invasive visualization of the internal meso-structure that allowed to obtain the changes of real meso-structure during a continuous deformation process.
4. Macroscopic numerical simulation results by FEM of large reinforced concrete elements by means of the elasto-plastic model with Drucker-Prager criterion in compression and with the Rankine criterion in tension was used. To properly describe strain localization in concrete, the model was enhanced in a softening regime by a characteristic length of micro-structure by means of a non-local theory. In addition, the bond-slip law between concrete and reinforcement was also assumed.

I was awarded for my scientific work:

1. In 2013: scholarship for young PhD researchers for scientific achievements within "Center for Advanced Studies – development of interdisciplinary PhD studies at Gdańsk University of Technology in key areas in the context of the Europe 2020 Strategy objectives" POKL.04.03.00-00-238/12 for the academic year 2013/2014.

2. In 2014: the Gdańsk University of Technology Rector's Award for the team's academic achievements.
3. W 2015: distinction in the category of technical sciences in the competition for the Branch Award of the Polish Academy of Sciences in Gdańsk for young scientists for the best creative work published.

My current Hirsch index: *h*=7, the sum of all citations: 223 (without self-citations: 185) according to Web of Science on 28.02.2019.

5. Description of other academic and research achievements

<u>Before obtaining PhD degree</u>

After I graduated, I started the PhD studies at the Faculty of Civil and Environmental Engineering. At the same time, in 2006, I started my work as an assistant. From the very beginning I was involved in modelling the behaviour of concrete and reinforced concrete elements within continuum mechanics by taking strain localization into account. In the initial phase of my scientific work, I concentrated on a number of experimental studies regarding the determination of the material strength and measurements of the shape and width of the strain localization zones in concrete elements subjected to bending using the non-invasive Digital Image Correlation (DIC) technique, based on measurements of displacements on the surface of concrete. Afterwards, I dealt with numerical analyses of strain localization in concrete and reinforced concrete subjected to tension and bending by means of different constitutive models. Numerical simulations were carried out in Abaqus using three different constitutive models: elasto-plastic, isotropic damage and smeared-crack. In order to properly describe strain localization phenomenon, all constitutive models were enhanced in a softening regime by a characteristic length of microstructure with the aid of a non-local theory. Due to the DIC technique, the characteristic length of microstructure (an important parameter in non-local theories) was determined. Macroscopic, mesoscopic and combined macro-mesoscopic simulations were carried out. At the meso-scale concrete was described as a three-phase material composed of aggregate, cement matrix and ITZs.

The title of my PhD thesis was "Macroscopic and mesoscopic modelling of strain localization in concrete". It was defended on 11 March 2011. The thesis included:

1. Description of strain localization in concrete.
2. Description of concrete properties and constitutive laws used for modelling the behaviour of concrete.
3. Experimental investigations for determining the width and shape of strain localization zones on the surface of notched concrete beams subjected to three-point bending. To measure displacements on the surface of concrete elements, a non-invasive digital image correlation (DIC) technique was used.
4. Numerical analyses of strain localization in concrete and reinforced concrete elements by means of constitutive models formulated within continuum mechanics using a macroscopic, mesoscopic and combined macro-mesoscopic approach. Numerical analyses by FEM were conducted using three different constitutive models: elasto-plastic, isotropic damage and smeared crack. In order to properly describe strain localization, the constitutive models were enhanced in a softening regime by a characteristic length of microstructure with the aid of non-local theory.

5. Numerical determination of representative volume element (REV) during uniaxial tension of concrete described as a three-phase material composed of aggregate, cement matrix and ITZ zones. Computations were performed using an isotropic damage model with non-local softening. The existence of RVE was discussed using a standard approach. In addition, two original methods of the determination of REV during uniaxial tension of concrete were proposed.
6. Comprehensive numerical calculations of notched concrete beams subjected to three-point bending using a combined macro-meso approach. An isotropic damage model with non-local softening was used. The influence of the beam size, distribution, volume, shape and size of aggregate grains and size of the characteristic length on the width and shape of strain localization and force-deflection curve was analyzed in detail.

The innovative points concerned:

1. Identification of a characteristic length of microstructure by means of comparative numerical computations FEM and experimental investigations using the Digital Image Correlation (DIC) technique.
2. Numerical computations of the Representative Volume Element (RVE) in concrete subjected to uniaxial tension.
3. Numerical meso-simulations of strain localization in concrete described as a heterogeneous three-phase material.

Some of the experimental and computational results from my thesis were published in 3 journals from the JCR list:

[1] Skarżyński, Ł, Syroka, E., Tejchman, J., 2011. Measurements and calculations of the width of the fracture process zones on the surface of notched concrete beams. *Strain*, 47, 319-332 (Appendix 5, item II.A.1).
[2] Skarżyński, Ł., Tejchman, J., 2010. Calculations of fracture process zones on meso-scale in notched concrete beams subjected to three-point bending. *European Journal of Mechanics/A Solids* 29, 746-760 (Appendix 5, item II.A.2).
[3] Skarżyński, Ł., Tejchman, J., 2012. Determination of representative volume element in concrete under tensile deformation. *Computers and Concrete*, 9(1), 35-50 (Appendix 5, item II.A.3)

and in the conference materials:

1. *AMCM* in Łódź in 2008 (Appendix.5, item II.L.1 i II.L.2).
2. *CMM* in Zielona Góra in 2009 (Appendix 5, item II.L.3).
3. *COMPLAS* in Barcelona in 2009 (Appendix.5, item II.L.4).
4. *ECCM* in Paris in 2010 (Appendix.5, item II.L.5).
5. *EURO-C* in Rohrmoos/Schladming in 2010 (Appendix.5, item II.L.6).
6. *CMM* in Warsaw 2011 (Appendix.5, item II.L.7).
7. *ECCOMAS* Vienna in 2012 (Appendix.5, item II.L.9).

During the conference CMM in Zielona Góra, I achieved the second award for the best paper presented by a young researcher (Appendix 5, item II.K.1).

My other scientific activity concerned the practical use of the acquired knowledge on experimental research and numerical simulations with advanced computational models in engineering problems. I performed numerous projects, technical opinions and expertizes. The most interesting expertize for the industry concerned the diagnostics of building structures and projects of repairs, renovations and modernization of existing buildings (Appendix 5, items II.B., II.E.4, II.F. and III.M.).

<u>After obtaining PhD degree</u>

The additional scientific achievements after obtaining PhD complemented my basic scientific activity. Some of them were a continuation of the PhD studies while the others concerned entirely new problems. They were divided into the following issues:

D. Numerical simulations of reinforced concrete elements.

E. Analyses of different material meso-structures using X-ray micro-computed tomography system Skyscan.

D. Numerical simulations of reinforced concrete elements

The main aim of numerical simulations was the description of strain localization and an associated size effect in concrete beams with longitudinal reinforcement (without stirrups) subjected to bending. An isotropic damage model with non-local softening and bond-slip law between concrete and steel was used. Numerical results were compared with corresponding experimental tests carried out by Walraven and Lehwalter in 1994 in terms of the material strength as well as location and spacing of strain localization zones. The FEM simulations revealed satisfactory agreement of the material strength for beams of different height and allowed to capture a size effect phenomenon observed in laboratory experiments. The calculated spacing of localized zones increased with increasing characteristic length, softening rate and beam height and decreasing fracture energy and bond stiffness. The calculated and experimental spacing of localized zones was significantly smaller than from analytical formulae. The obtained results were published in one journal from the JCR list (Appendix 5, item II.A.4):

[1] Marzec, J., Skarżyński, Ł., Bobiński, J., Tejchman, J., 2013. Modelling of reinforced concrete beams under mixed shear-tension failure with different continuous FE approaches. *Computers and Concrete*, 12(4), 377-392.

They were also presented as the oral presentation at international conference *ECCOMAS* in Vienna in 2012 (Appendix 5, item II.L.9).

E. Analyses of different material meso-structures using X-ray micro-computed tomography system Skyscan

The main goal of my works were the analyses of microstructures of different materials using the micro-computed tomography which is a non-invasive method that enables a qualitative and quantitative evaluation of meso-structural components. The scope of micro-CT research works concerned the following materials and elements:

1. Titanium implant in pig's knee – the aim of the study was to determine the bone structure density in the neighborhood of the implant. The obtained 3D images were used to improve the implant's geometry and methods of its application.
2. Human's jaw - the aim of the study was to determine the geometry of the jaw. The obtained 3D images were used to create a computational model for analyses of a safe extraction of the eight teeth.
3. Pills - the aim of the study was to determine the porosity in pills of different geometry produced during various technological processes. The obtained 3D images were used for the shape and technological process optimization.
4. Injectors for cars – the aim of the study was an analysis of internal structure and verification of the accuracy of a production process.
5. Elements of car bumpers - the aim of the study was an analysis of material porosity for the technological process optimization.
6. Polymers - the aim of the study was an analysis of internal structure. The obtained 3D images were used to improve the manufacturing process of components.

The results were published in one journal from the JCR list (Appendix 5, item II.A.5):

[1] Szewczykowski, P.P., Skarżyński, Ł., 2019. Application of the X-ray micro-computed tomography to the analysis of the structure of polymeric materials, *Polimery*, 64(1), 12-22.

They were also presented as the oral presentation at international conferences: *Bruker Micro-CT User Meeting:* in Bruges (2015), Luxembourg (2016), Brussels (2017) and Ghent (2018) (Appendix.5, items II.L.13-16).

6. Didactic activities

Since the beginning of my employment at the Gdańsk University of Technology (in 2006), I have the classes on full-time and part-time studies in civil engineering (Appendix. 5, item III.J):

1. Building Construction I (undergraduate studies) – tutorials and projects.
2. Building Construction II (undergraduate studies) – tutorials and projects.
3. Renovation and Modernization of Buildings (graduate studies) – lectures, tutorials and projects (the person responsible for the subject),
4. Diagnostics of Masonry, Concrete and Wooden Structures (graduate studies) – lectures, tutorials and projects (the person responsible for the subject),
5. Seminar on Civil Engineering (graduate studies) – seminar (in English).

I prepared the program of two following classes: Renovation and Modernization of Buildings and Diagnostics of Masonry, Concrete and Wooden Structures. In 2012, I achieved the second award of the Dean of the Faculty of Civil and Environmental Engineering at the Gdańsk University of Technology for the best teacher at the faculty (Appendix 5, item III.D.1).

Since 2011 I was the supervisor of 36 and the reviewer of 36 bachelor theses and the supervisor of 17 and the reviewer of 16 master theses on full-time and part-time studies (Appendix 5, item III.J).

7. Organization activities, scientific cooperation and popularization of science

At present I am the coordinator of the international research project „Development of boron-infused basalt-fibre reinforced concrete for nuclear and radioactive waste management applications". This is the National Science Center (NCN) grant UMO-2017/26/Z/ST8/01240 financed from M-ERA.NET Call 2017. The project started on 31 July 2018 and will last for 24 months. The project is realized within an international consortium including the University of Tartu, US Basalt Corporation, Laiers Grupp OÜ and BasaltEst OÜ (Appendix 5, item II.J).

From 2015, I am the Head of Laboratory of Material Engineering and Building Physics. The main aim of the Laboratory is experimental research supporting the scientific work of the Department and support of the construction industry through the works related to the diagnostics and optimization of engineering structures. To achieve this goal the Laboratory offers its services in the field of materials research, numerical analysis and technical advice during the construction works. Moreover, in the Laboratory educational activities are conducted and experimental investigations within Bachelor's and Master's theses are carried out.

Since 2016, as part of the Baltic Science Festival at the Gdańsk University of Technology, I organized trips and made demonstrations for kindergarten groups under the title „Little curious people visit Gdańsk University of Technology – trip for future engineers". As a part of this project, I organized tours at the campus through the most interesting attractions of the Baltic Science Festival. The trips always end with a visit to the laboratory, a presentation of the research equipment and a demonstration of some experimental tests. So far over 250 children visited the Gdańsk University of Technology (Appendix 5, item III.A.).

I am the active participant of several scientific conferences (Appendix 5, items II.L and III.B). I took part in 3 national conferences and 18 international conferences. I held in total 16 oral presentations. The most important conferences that I attended were: *Computational Modelling of Concrete Structures EURO-C* (2010, 2014), *Conference on Computational Plasticity COMPLAS* (2009, 2015), *AMCM* (2008, 2011), *Bruker Micro-CT User Meeting* (2015-2018), *European Conference on Computational Mechanics ECCM* (2010). *Conference on Computer Methods in Mechanics CMM* (2009), *European Congress on Computational Methods in Applied Sciences and Engineering ECCOMAS* (2012), *International Conference on Experimental Mechanics ICEM* (2014), *International Conference on Fracture Mechanics of Concrete and Concrete Structures FraMCoS-8* (2013), *International Conference on Computational Modeling of Fracture and Failure of Materials and Structures CFRAC* (2015).

Since 2009 I prepared 12 reviews of papers submitted to journals from the JCR list (Appendix. 5, item III.P):

- European Journal of Civil and Environmental Engineering – 2011.
- Journal of Engineering Mechanics – 2012.
- Engineering Fracture Mechanics – 2013.
- Engineering Fracture Mechanics – 2015.
- International Journal of Fracture – 2016.
- Journal of Testing and Evaluation – 2017.
- Journal of the European Ceramics Society – 2017.
- Construction and Building Materials ×2 – 2018.
- Materials Characterization – 2018.
- Journal of the European Ceramics Society – 2018.
- Materials – 2019.