UNIVERSITA' DEGLI STUDI DI NAPOLI FEDERICO II

DIPARTIMENTO DI STRUTTURE PER L'INGEGNERIA E L'ARCHITETTURA
CORSO DI DOTTORATO DI RICERCA IN
INGEGNERIA STRUTTURALE GEOTECNICA E RISCHIO SISMICO

XXXVI CICLO

Il sottoscritto dott. Francesco Marmo

(RTD - B) afferente al Dipartimento di Strutture per l'Ingegneria e l'Architettura

S.S.D. (ICAR/08 Scienza delle Costruzioni)

CHIEDE

di essere inserito tra i possibili tutor di studenti di dottorato per il XXXVI ciclo.

1. Curriculum sintetico del proponente (max 500 parole)

Current position
Since 28th December 2018 Francesco Marmo is RTD-B (SSD ICAR/08), at the Department of Structures for Engineering and Architecture, University of Naples Federico II. On 28th May 2019 he obtained the National Scientific Qualification as Full Professor (SC 08/B2).

Education
14th Jan. 2008: PhD in Construction Engineering at the University of Naples Federico II. Title of the PhD Thesis: *A Fibe-Free approach to the inelastic analysis of reinforced concrete structures*. During his doctoral studies Dr. Marmo spent 13 months at the Department of Civil and Environmental Engineering of the University of California at Berkeley, where he collaborated with prof. R. L. Taylor, prof. F. C. Filippou and passed the exam of Computational Mechanics held by prof. F. Armero obtaining the maximum grade.
24th Oct. 2004: MS with honours in Civil Engineering at the University of Naples Federico II.

Research
2013 – 2018: He covered the position of RTD-A (SSD ICAR/08), at the Department of Structures for Engineering and Architecture of the University of Naples Federico II.
2008 – 2013: He collaborated (2 collaboration positions, 1 post-doc fellowship, 2 research fellowship) with the Department of Structural Engineering of the University of Naples Federico II and with the Department of Technologies of the University of Naples Parthenope.
2008 – 2019: He participated to 12 founded research projects regarding the nonlinear

analysis of structures and the structural safety of heritage buildings and urban areas exposed to seismic risk.
He is author of 34 papers published on peer reviewed international journals (350 cites, H-index 11) and 49 papers published on international and national conference proceedings. His researches regard assorted topics of computational mechanics applied to RC and masonry structures, contact mechanics and elastic inclusion problems. His research interests include the nonlinear analysis of RC cross sections, frames and shear walled structures, FEM formulations for modelling geometric and mechanical nonlinearities, elastic solutions for transversely isotropic solids, potential theory, form finding of shells, limit analysis of arches and vaults.

Teaching
Since 2016 he teaches the courses: *Elasticity and Fracture of Materials / Continuum Mechanics* (BEng in Science and Engineering of Materials); *Continuum Mechanics* and *Finite Element Analysis of Structures* (MS Structural and Geotechnical Engineering).
Since 2014 he offered several seminars and short courses for MS and doctorate students at the Princeton University, International Centre for Mechanical Sciences (CISM-Udine), Technical University of Cluj-Napoca, University of Naples Federico II.
Since 2017 he teaches an international short course on Seismic Analysis of RC Structures using OpenSees offered in succession at several Universities worldwide.

2. Dottorandi dei quali il proponente è stato tutor nell'ultimo triennio

n. _____	*specificare tipologia di borsa: ateneo, pon, por, senza borsa, ecc.* _____

3. Titolo della ricerca proposta

Mechanical behaviour and digital fabrication of compliant shells

4. Area tematica

Ingegneria Strutturale

5. Sintesi del progetto di ricerca (max 500 parole. Stato dell'arte, obiettivi e breve programma previsto per le attività e)

Double curvature shells are characterized by their high stiffness, which is strictly related to their geometry. For this reason, they are traditionally considered among the most efficient structural elements. They are also the basis for a new typology of structures: compliant shells. These are ideal candidates for producing compliant mechanisms, i.e. flexible mechanisms that transfer an input force or displacement without moving parts, which instead, require assemblage, lubrification and rupture of joints. Indeed, these mechanisms are already employed by biological organisms, mostly plants and invertebrates, in order to generate movements without the need of any complex musculoskeletal system.

The present research project has the objective of comprehending the mechanical behaviour and study the industrial fabrication of thin double curvature compliant shells. This research activity is characterized by a multidisciplinary interaction between the topics of structural mechanics, biological sciences and industrial design; Specific competences are employed to model the complex mechanical behaviour and implement biomimetic design processes within the framework of digital fabrication (Industry 4.0).

The research program is organized as follows:

Phase 1: Analysis of plant and invertebrate kinematics. The research will focus on the study and classification of the mechanisms implemented by these organisms to obtain movements by deforming their curved parts. This phase of the research will be conducted in collaboration with prof. C. Langella and doct. V. Perricone (Vanvitelli University).

Phase 2: Development of a computational method for the numerical analysis and form finding of equilibrated configurations of compliant shells subjected to external loads and internal self-stresses. A method based on the so-called dynamic relaxation of spring-particle systems, already employed for the analysis of lace structures, will be extended to include two-dimensional elements.

Phase 3: Analysis of scale effects on the performance of compliant shells. This issue, to be investigated in collaboration with prof. S. Adriaenssens (Princeton University), is particularly relevant for the design of compliant shells since all examples coming from biological organisms are characterized by a scale that is two orders of magnitude smaller than typical mechanical and civil engineering structures. It is expected that their employment at larger scales, where gravity loads have a significant effect on deformable bodies, will require high strength materials, such as composite materials or amorphous

metals.
Phase 4: Study of the role of curvature on the number and shape of stable and unstable equilibrated configurations, also considering the effect of self-stresses induced by fabrication processes. Current studies, conducted in collaboration with the research group of prof. Adriaenssens, have shown that, for lace structures, multiple stable configurations can be produced by self-stresses associated with over- and under-curvatures introduced by the fabrication process.
Phase 5: Development of design methodologies and industrial fabrication processes of compliant shells. The cases of compliant shells having constant or continuously varying gaussian curvature will be addressed and the possibility of producing shells having piecewise constant curvature obtained by folding flat elements will be investigated. Fabrication issues will be tackled in collaboration with an industrial partner that has a long experience in digital fabrication processes.

6. Eventuali pubblicazioni del tutor sul tema di ricerca (max 10)

1. F. Marmo. Form finding of shell structures by using membrane theory. In preparation.
2. V. Perricone, T. Grun, F. Marmo, C. Langella, M. D. Candia Carnevali, Constructional design of echinoid endoskeleton: a deep insight on the main structural components and their potential for biomimetic applications. Royal Society Open Science. Submitted.
3. S. Sessa, F. Marmo, N. Vaiana, D. De Gregorio, L. Rosati, Strength hierarchy provisions for transverse confinement systems of shell structural elements. Composites Part B, 163:413-423, (2019).
4. F. Marmo, C. Demartino, G. Candela, C. Sulpizio, B. Briseghella, R. Spagnuolo, Y. Xiao, I. Vanzi, L. Rosati. On the form of the Musmeci's bridge over the Basento river. Engineering Structures, 191:658-673, (2019).
5. F. Marmo, V. Perricone, C. Langella, G. Pontillo, L. Rosati, Bioinspired design of shell structures: a lesson from echinoids. 60th Anniversary Symposium of the International Association for Shell and Spatial Structures, 9th International Conference on Textile Composites and Inflatable Structures, Form and Force, October 7-10, Barcelona, Spain. Carlos Lázaro, Kai-Uwe Bletzinger and Eugenio Oñate (eds.), (2019).
6. S. Gabriele, F. Marmo, V. Varano, About the funicularity of Velaroidal Shells. 60th Anniversary Symposium of the International Association for Shell and Spatial Structures, 9th International Conference on Textile Composites and Inflatable Structures, Form and Force, October 7-10, Barcelona, Spain. Carlos Lázaro, Kai-Uwe Bletzinger and Eugenio Oñate (eds.), (2019).

7. V. Perricone, F. Marmo, A. Gloria, C. Langella, G. Pontillo, M.D. Candia Carnevali. Constructional design of sea urchins test: in progress study for promising biomimetic applications. **Contributo premiato** dal 50° Congresso della Società Italiana di Biologia Marina, Livorno, 10-14 giugno 2019.
8. V. Perricone, F. Marmo, A. Gloria, C. Langella, M.D. Candia Carnevali, L. Rosati. Mechanical design of sea urchin test: an adaptive strategy for flexural resistance. 8th Congress of the Italian Society of Evolutionary Biology. Padova 1-4 September 2019.
9. F. Marmo, L. Rosati, Form finding of compressed shells by the Thrust Membrane Analysis. Proceedings of the IASS Symposium 2018 Creativity in Structural Design, July 16-20, 2018, MIT, Boston, USA. Caitlin Mueller, Sigrid Adriaenssens (eds.), (2018).
10. F. Marmo, L. Rosati. Reformulation and extension of the thrust network analysis. Computers & Structures, 182:104-118, (2017).

7. Eventuali progetti di ricerca finanziati in cui l'attività si inserisce

8. Eventuali fondi disponibili a supporto dell'attività del dottorando (escluso finanziamento borse)

The fees and living expenses for the first month of the visiting period at the Department of Civil and Environmental Engineering of the Princeton University (see point 9 below) will be covered by prof. Adriaenssens of the University of Princeton with funds pertaining to the project entitled *Harnessing non-linear mechanics and robotics for structural innovation in architecture* (Source of Support: Global Collaborative Network (GCN); Total Award Amount: $224,050; Total Award Period Covered: 9/1/20-8/31/23; Location of Project: Princeton University).

The research activity, to be developed in collaboration with the industrial partner, will be conducted at its laboratory (see point 10 below). The employment of numeric control milling machines has an estimated cost of 50-80€ machine-hours and 30-50€ man-hours. Resources of AUTOMA Pantografi will cover these costs.

9. Informazioni relative ad un periodo di ricerca all'estero (minimo tre mesi) previsto per il dottorando (*indicare Università/ente di ricerca e docente/ricercatore di riferimento* con indirizzo mail) (max 300 parole)

The research activity pertaining to the phase 3 will be conducted during a period of three/six months that the candidate will spend at the Department of Civil and Environmental Engineering of the Priceton University, in collaboration with the research group of prof. Sigrid Adriaensens. Prof. Adriaenssens' research focuses on lightweight surface systems and how they can be optimized and realised to interact with extreme structural or environmental loading. This includes research on flexible and rigid shells and plates, submerged flexible membranes and nets, and metamaterials with applications for a resilient urban environment.
The goal of this collaboration will be that of gaining insight in the influence of gravity-induced forces on the ability of shells to perform as compliant mechanisms through an order-of-magnitude approach. The dimensions and mechanical characteristics of existing shells will be identified and catalogued in order to determine a non-dimensional parameter that characterizes the most likely deformation mode of the shell, i.e., bending or stretching, when subjected to gravity loads. This parameter will be used to determine the limit at which bending deformations due to gravity appear in the shell and measure the scale at which compliant shells become highly susceptible to gravity induced deformations.

10. Eventuali collaborazioni con imprese/aziende sul tema di ricerca (max 300 parole)

Research activity of phase 5 will be conducted in collaboration with AUTOMA Pantografi srl (https://www.automapantografi.com/), active in the field of digital fabrication (Industry 4.0). This industry boasts several years of experience in production and industrial employment of numeric control milling machines. Their machineries are capable to produce, by means of a process named subtractive manufacturing, structural and mechanical elements characterized by a high degree of complexity and accuracy.
The goal of this collaboration is to apprehend the technical issues regarding the production of compliant shells by the principles of digital fabrication and subtractive manufacturing. The possibility of producing curved geometries by milling and folding plane sheets of amorphous metals will be investigated. It is known, from the scientific literature, that curved geometries can be obtained by folding planes along curved creases. The same happens when portions of a plane are cut out along curved boundaries and their edges are merged together. Hence, it is expected that the production of compliant shells can be put in practice by employing the principles of

origami and kirigami, consisting in folding, cutting and gluing planar sheets to produce complex forms. Thanks to the collaboration with such an experienced industrial partner, the design methodology will be adapted to and corrected according to the practical problems arising from the production process.

Napoli, 13/2/2020

FIRMA

Il presente modulo va compilato in ogni sua parte ed inviato all'indirizzo di posta elettronica phd.dist@unina.it entro e non oltre **venerdì 14/02/2020**.