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APCOM2019 のご案内

岡田　裕　JACM 会長（東京理科大学）

The Asian Pacific Congress on Computational Mechanics 2019 (APCOM2019)が2019年12月18日（水）～21日（土）にTaipei International Convention Center, Taipei, Taiwanで開催されます．
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岡田　裕　JACM 会長（東京理科大学）

JACM 総会ならびに 2019 JACM Awards 授賞式を APCOM2019開催期間中に開催致します．開催日時と会場の詳細については決まり次第，メールマガジンやメール配信によりお知らせします．
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JACM 関連若手研究者の紹介（その 8）

JACM に関連する若手研究者の方々を順次紹介しています．
その第 8 回として，Tinh Quoc Bui 様（東京工業大学）と塚原 隆裕 様（東京理科大学）をご紹介いたします．

COMPUTATIONAL AND THEORETICAL MODELING FOR FAILURE IN QUASI-BRITTLE MATERIALS, COMPOSITES, AND POROUS MEDIA

Tinh Quoc Bui（Tokyo Institute of Technology）

Thank you very much for being elected as The 2018 JACM Award for Young Investigators in Computational Mechanics. It was a great honor for me to be the recipient of this award. Thank you to those who nominated me and supported my nomination. A very special thanks to the JACM for giving me a chance to introduce my study in the JACM Mail Magazine No. 44. This is my great pleasure to share all of you some of typical results that have been conducted over the past ten years.

Our research group on Computational Mechanics at the Department of Civil and Environmental Engineering, School of Environment and Society, Tokyo Tech is devoted to the study of a wide range of physical and mechanical phenomena and engineering problems in solids, multiphase composites, and porous media. Much of the research works conducted within our group is based on theoretical modeling and advanced computational methods development, computational mechanics, taking into account the behavior of solids and advanced complex and multi-phase materials under the actions of various types of loading. The problems considered within the group are often, in whole or in part, interdisciplinary in nature, reflecting a combination of methodologies, concepts and principles usually spanning several areas of civil and mechanical engineering, material sciences, physics, mathematics, and computer science. We are particularly interested in modeling softening behavior, discontinuities, topological and geometrical changes, delamination, moving boundaries, localized failure and instabilities in different materials such as solids, smart functional materials, laminated composites, and porous materials, by developing theoretical damage models and efficient and accurate numerical techniques.

I started pursuing pure mathematics with emphasis on partial differential equations for my undergraduate at the National Vietnam University-HCMC in 1996, two years later of the university I changed my study subject to computational solid mechanics instead. Neither pure math nor computational mechanics, which one is better than the other, it actually changed my professional career. I finally completed my bachelor with a research topic on development of a symbolic computer code using MAPLE programming language for finite element analysis of carbon-fiber laminated composite plates. I then pursued my higher educations in civil and mechanical engineering in different countries in Europe. I performed my master thesis at the University of Liège, Belgium under the guidance of Dr. Marc Duflot (he is now at MSC Software Corporation) about development of particle meshfree methods for error estimations and duality analysis. Soon after, I joined to work on an active research team led by Profs. H.J. Böhm and

F.G. Rammerstorfer at the Institute for Lightweight Design and Structural Biomechanics, Vienna University of Technology, Austria, and conducted my doctoral research work focusing on development of some non-traditional computational approaches into modeling failure behavior of spot-welds, an important joining technique that is currently used in fabricating virtually all car bodies. The studies are based on the capabilities of finite element analysis and mesh-independent modeling of fastener/connector in the explicit FE code ABAQUS/Explicit, high-performing computing, stochastic analysis, and soft-computing methods (e.g., artificial neural networks, machine learning, data mining, and genetic algorithm) [1].

At the Center of Structures and Material Sciences, Department of Mechanics and Materials Processing, Ecole Nationale Superieure des Mines de Saint-Etienne, France, where I worked as a postdoctoral researcher for an industrially funded project, I developed computer codes and subroutines integrated into in-house Zebulon finite element solvers for delamination (bonding/debonding) in carbon-fiber laminated Z-pin joints under pull-out, shear, and flexure dynamic loading conditions. This Z-pin joining techniques play a crucial role in many engineering applications including aerospace and automobile. Fig. 1 shows two types of Z-pin failure by experimental testing.

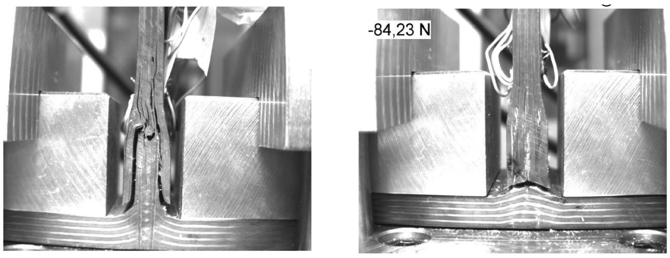

Fig. 1 Z-pin interface failure on the web (left) and crack between the web and flange (right).

At the Department of Civil Engineering, University of Siegen, Germany, where I subsequently worked as postdoctoral fellowship and senior researcher, my main research goal there was to modeling of dynamic fracture mechanics in multiphase smart functional materials (e.g., functional piezoelectric and magnetoelectroelastic) under thermal environment by enrichment techniques (e.g., extended finite elements and isogeometric analysis). Smart functional materials offer many opportunities for engineers and designers to develop novel devices and intelligent structures, for instance, transducers, smart sensors, actuators, lasers, supersonics, and microwaves. The key features lie in the surprising coupling effects among mechanical, electrical, and magnetic fields. Due to the brittle in nature, their imperfection or defects are unavoidable. I successfully conducted 04 research projects funded by DFG and DAAD, and achieved results have been published in a number of scientific journals, e.g., [2, 3] .

In 2014, I honorably received a JSPS postdoctoral fellowship (standard program), and two years later I was again awarded another JSPS postdoctoral fellowship for senior scientist (pathway program), both hosted by Prof. Sohichi Hirose. During that time at Tokyo Tech, I conducted several problems, for instance, cohesive crack growth in terms of XFEM for quasi-brittle concrete [4], fatigue crack growth under variable-amplitude cyclic loading, adaptive local-mesh refinement XFEM for 2D and 3D cracks in solids and functional materials, transient crack analysis of generalized stress intensity factors for multiphase smart composites by extended isogeometric analysis [5], hybrid phase field model for dynamic crack growth in functionally graded materials [6], or modeling unsaturated flow problems in porous media using isogeometric analysis with non-uniform rational B-splines basis functions [7]. Fig. 2 depicts the water content for irrigation by furrows in which the contour lines represent the wetting front dependent on the situation of moisture content. At low moisture level where water fronts beyond 30 cm in depth, the IGA offers smooth and less oscillation in comparison with the conventional approaches (not shown here) [7].

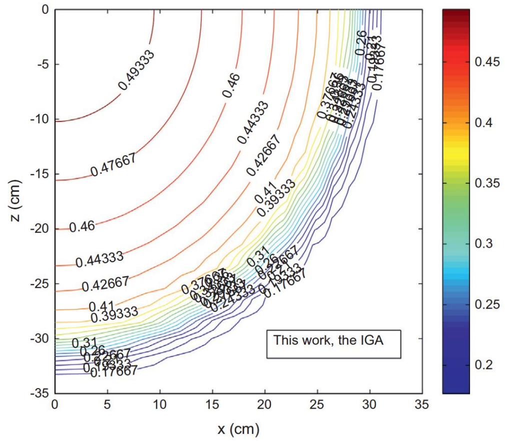

Fig. 2 Water content for irrigation by furrows computed by the isogeometric analysis [7].

In 2016, I started establishing my research group at Tokyo Institute of Technology concentrating on Computational Mechanics and Fracture Modeling with several undergraduate and graduate students. The group size is now getting larger and larger. Generally, the ultimate goals or the main objectives of our research group devote to fourfold: (a) to discover new physical phenomena relevant to scientific engineering problems; (b) to improve and enhance technological developments in terms of numerical simulation using modern techniques; (c) to solve engineering problems of a broad range of industries; and (d) to provide effective tools of numerical solutions to explore phenomena and predict behavior that may be used to advance concepts and design in practical applications.

Quasi-brittle failure concerns a large number of geomaterials such as rock, concrete, or limestone, which are of great importance in many engineering applications especially in infrastructure systems. We have proposed a novel smoothing gradient-enhanced damage model with evolving anisotropic nonlocal interactions, which goes beyond certain limitations of conventional approaches, for localized failure in quasi-brittle materials [8]. This new approach owns many desirable features as it can eliminate non-physical spurious damage growth; control softening behavior through fracture energy and characteristic length, and model well compressive shear-band problems. Fig. 3 shows mode-I failure simulation of three-point bending limestone beams, in which three sizes of beams have been conducted and computed force-displacement responses are compared with experimental data. The damage evolution grows from the notch at the middle of the beams. This new gradient-enhanced damage model has been now extended to solve some more complicated problems, for instance, one is to take into account the dynamic rate-dependent effect and another is to analyze failure response of porous media in geomechanics applications. For rate-dependent gradient damage model, a dynamic damage model should be developed. For transport and damage in porous media, a nonlocal damage-poroelastic model should be introduced, and a monolithic algorithm in terms of finite element method which must be developed to solve coupled systems with a displacement-pressure-regularized permeability element formulation. Both these works have been under developments.

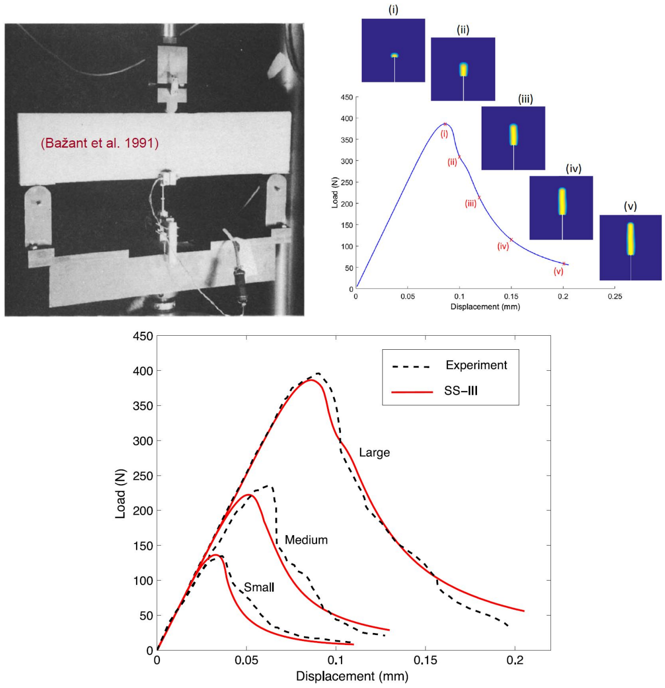

Fig. 3 Three-point bending limestone beams and numerical results [8].

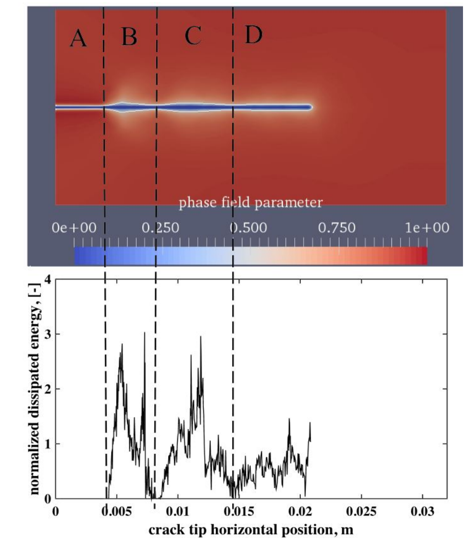

Fig. 4 Correlation between phase field distribution and dissipated energy [9].

In line of the continuum damage model, we have studied alternative emerged fracture mechanics method, the phase field model, which goes beyond certain limitations of LEFM theory of Griffith. For instance, we developed a rate-dependent hybrid phase field model for dynamic crack propagation in functional composites, exploring the dissipated energy dependent crack velocity, one of the important aspects of dynamic fracture [9]. Fig. 4 sketches the correlation between dissipated energy, which is normalized by fracture energy, and the phase field distribution for a polymethylmethacrylate (PMMA) rectangular plate. Basically, the evolution of crack can be interpreted through the representation of the normalized dissipated energy. As indicated in the figure, the zone A indicates the initial crack, when loaded, the cracks starts propagating at which the energy dissipated rapidly as shown in zone B. In this zone, the crack smeared out with the band width increasing to the maximum value and then decreases to the constant band width as the initial state. The crack here does not show to be branching since the energy dissipated at crack-tip is not strong enough, see zone C. At zone D, the crack reaches the saturated velocity without the oscillation in the crack band width.

In the past decades, the failure in layered heterogeneous composites and structures has been studied by many researchers due to their critical role in mechanics and physics of solids. We introduced a new methodology for better describing interface cracks in 2D and 3D by a regularized interfacial transition zone in the context of variational phase field model [10]. One of the main purpose of this new model is to circumvent drawbacks of sharp-transition models as the jumps at mismatch material and geometry discontinuity effects can be treated in a straightforward manner. Fig. 5 depicts the crack growth in 3D layered heterogeneous beam and shows a comparison of crack morphologies between the computed phase field model and experiment for a multi-layered structure.

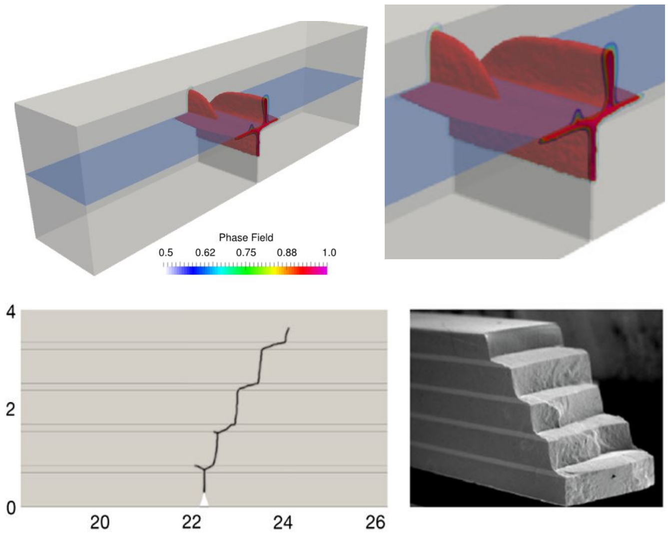

Fig. 5 Crack growth in 3D layered structure (top) and comparison of crack morphologies between phase field model and experiment for a multi-layered structures (bottom [10].

We have conducted 3D micromechanical modelling of progressive failure in fiber-reinforced composites by using the phase field model. One of the advantages of the phase field model in modeling localized failure problems is its capability to model crack behaviors without requiring any additional ad-hoc fracture criteria or crack tracking strategy. Conventional numerical approaches such as discrete approaches for modeling a complete progressive failure of fiber-reinforced composite are still challenging, and most of numerical methods are designed for single failure mechanism. Generally, composite laminates can be studied at three length scales (i.e., macro-, meso- and micro-scales). This study is particularly devoted to micro-scale failure modeling. Fig. 6 shows the interface phase field of the 30º/90º plies specimens and crack phase field at the end of the loading stage (top) and a comparison of crack patterns (i.e., interface debonding and matrix cracking) between the phase field model and experiment (bottom).

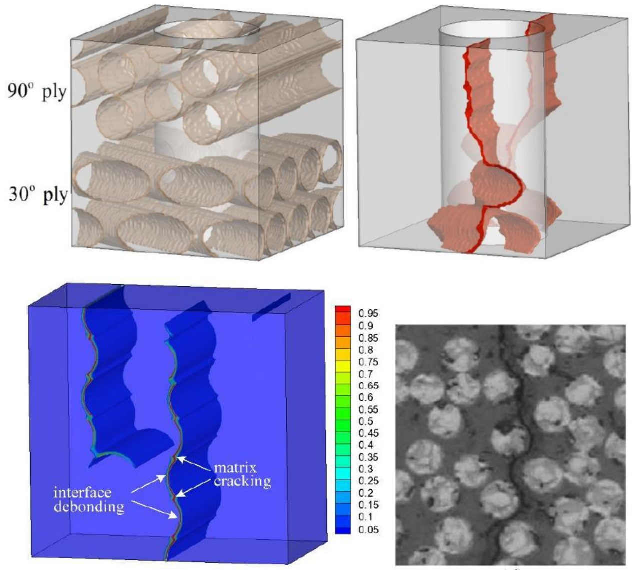

Fig. 6 Interface phase field crack of a 30/90 plies specimen (top) and comparison of crack patterns between numerical approach and experiments.

We recently computed the phase field model to capture and investigate complex fracture behavior in cement-based materials at early-age [11]. We developed a model that consists of coupling the most important chemo-thermo-mechanical processes to describe temperature evolution, variation of hydration degree, and mechanical behavior. In fact, early-age shrinkage and hydration heat induced defects in concrete have been a major research area in the past few decades. Since the change of mechanical properties of early-age concrete is relatively fast, and is largely dependent on physical and mechanical processes (i.e., hydration), modeling of such complex fracture in cement-based materials at early-age stage by means of conventional numerical approaches is not a trivial task. Fig. 7 represents the computed results of crack growth, temperature, and hydration evolution for conducting crack in the L-shaped structure.

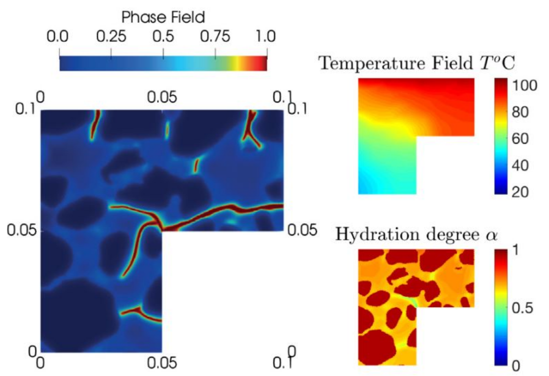

Fig. 7 The evolution of phase field, temperature, and hydration of a L-shaped structure at a certain time step.

I have presented in this note some major numerical results that have been conducted either individually or collaboratively. Computational and theoretical modeling works for failure problems in composites, solids, or porous media are one of the fields where computer-based simulations have been constantly used. It is because that numerical simulations required for basic design is roughly put to practical use. The team at Tokyo Tech has a vast expertise in the area of computational mechanics as it has been advancing computational fracture mechanics for many years. We now have in hand many of the ingredients for pursuing the mentioned research area. The well support from the Department of Civil and Environmental Engineering, the School of Environmental and Society, and Tokyo Tech, has greatly helped us in conducting the study as they have very strong research capabilities in the areas of concrete structures, steel structures, geomechanics, geotechnical engineering, and so forth. However, we have learnt that there are many other unsolved problems that still remain and challenge us, and what difficult tasks cannot be analyzed with commercial software, the group for sure will continue to develop new and effective numerical approaches and more appropriate theoretical models that allow us to solve the problems in better way.

In future, apart from other favorite research areas such as fracture in solids and functional composites [12-13] and continuum damage model [8, 14], we are particularly more focusing on theoretical and computational modeling approaches for, for instance, multiscale fracture in porous media, dynamic response, mass transport, and coupled systems, which are currently a prominent research topic. This certainly is a fascinating research area where several grand challenges of computational mechanics come together, e.g., multi-physics problem, multi-scale phenomena, or the interaction between mechanical phenomena and one or more diffusion problems.

In recent years, collaborations with the field of computational mechanics have been active, and in this way, we are conducting research on numerical simulation deeply and on a wide range of computational approaches. Please contact us if you are interested in conducting research for the degrees of mater, and doctoral, or postdoc programs.

Once again, I would like to thank the JACM for giving me a chance to share some of my research interests. Many thanks to all my former Advisors and Professors, my past and current Colleagues, Collaborators, Students, and to those who have been continuously supporting me.

"The experience of living in a different country and learning different approaches to scientific problems broadens your mind for research", said by Nick Luscombe, a computational biologist who found that moving from the UK to the USA for a postdoc was "an eye-opener". This interesting story from Science Magazine has impressed me a lot as it would be true that the experience living in different countries raised our own confidence, but also reinforced our appreciation of time to think through scientific problems.

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壁乱流亜臨界遷移の DNS 基礎研究

塚原 隆裕（東京理科大学）

卒業研究で初めて計算力学と CFD（数値流体力学）の世界に触れ，即座にその可能性と奥深さに惚れ込んでから早 17 年，主に DNS（直接数値計算）による乱流研究に携わって参りました．学生時も“携わった”と言うには少々おこがましく，実際には只々無我夢中でした．最早，“若手”というには（JSPS 科学研究費補助金・若手研究の応募枠に依れば）ぎりぎりの年齢となった私が, 2018 年 7 月に The JACM Young Investigator Award という栄誉ある賞を賜り，“大人の階段を登った”一人前の研究者として一層精進して参ろうと心新たに思う次第です．ご推薦ご選考を頂いた諸先生方には改めてお礼を申し上げます．望外にも, JACM メールマガジンにて小職の研究紹介の場を頂きましたこと，重ねて感謝申し上げます．

現在は，東京理科大学理工学部機械工学科に所属しておりますが，出身も同学科であり卒業研究から博士課程まで河村洋教授（現・東京理科大学名誉教授）のもとで DNS による壁乱流の研究に取り組んでおりました．卒研配属当時，“乱流”が研究テーマになるほどの深みがあるとは全く知らず，単にランダムノイズとしか認識しておりませんでした．学生時代は講談社ブルーバックス等の自然科学啓蒙書が好きで，当時から“決定論的カオス”や“非平衡現象”，そして“パーコレーション”など自然の無秩序の中にある秩序に言い知れぬ魅力を感じておりました．この無知で好奇心しかなかった私に，河村先生からは壁乱流に潜むカオスを卒論テーマとするご提案を頂きました．一年間熱中して挑んだものの敵は手強く，結局，研究結果がカオスになったことは良い思い出です．院生時代はターゲットを変えて，壁乱流に潜む大規模な準秩序構造を DNS により調査しました．ここで，DNS の簡単な紹介を致しますと，乱流モデルを一切用いずに流れの支配方程式（Navier-Stokes 方程式）を直接に計算する方法であり，内在する乱流構造の全容を捉える“大きな計算領域”と最小渦（コルモゴロフスケール渦）も解像する“小さな要素（または格子幅）”を要するため計算負荷が膨大となります．一般的に産業界で使われる CFD ソフトウェアでは乱流モデルを用いた RANS 解析を行い，コスト軽減が図られています．例えば，走行する車の丸ごと計算には，RANS や LES（large eddy simulation）またはそれらのハイブリッドで行われます．これの DNS は現存の最速大型計算機を用いても困難であり，平行平板間流れや平板境界層などのカノニカルな壁乱流に DNS の適用範囲は限られています．しかし，DNS で得られた知見とデータベースは，乱流ダイナミクス解明と乱流モデル改善に役立てられ，大変に貴重なものとなります．閑話休題．大型ベクトル計算機を利用し，当時の世界最大級 DNS を実施した結果，私は院生時に平面クエット乱流の大規模構造や，亜臨界遷移の層流－乱流パターン形成を発見しました．これは，新計算手法の開発によるわけでなく，大規模並列計算を実施した結果であり，単に幸運に恵まれたのかもしれません．しかし，発見自体に気付けたことや，少し異常なパラメータ設定と知りながら“遊んで”みることが新発見に繋がり，日々乱流計算と向き合って成し得たこととも思います．肝要なのは探求心と好奇心…当然のことですが多忙な業務に惑わされ初心を忘れてしまわないよう，自戒の念を込めてのお話です．本メルマガ読者の先輩方には退屈な話でございました．

現在も継続して取り組む研究テーマの一つが，上述の「亜臨界遷移の層流－乱流パターン形成」です．一般的に，レイノルズ数（流速または寸法の指標）が大きくなると流れは秩序立った層流状態から，大小様々な渦を伴い非定常性・三次元性を有する乱流状態になります．流路形状が同じでも層流と乱流では，摩擦・伝熱・拡散性・混合性が顕著に異なるため，しばしば産業の場面で状態予測・制御の必要性に迫られます．その際，層流⇔乱流の切替わり，いわゆる臨界レイノルズ数の知識が重要ですが，この値は経験的にしか特定できず，大規模な実験や DNS に頼らざるを得ないことが大半です．カノニカル壁乱流の一つ，直円管内流れの臨界レイノルズ数は 2000～2300 程度と知られていますが，より厳密な特定（2040±10）に至ったのは最近のことです[1]．これには，壁乱流の亜臨界遷移（線形安定性理論による臨界値よりも低いレイノルズ数で，有限撹乱に起因する乱流遷移）で層流と乱流が空間的に共存し，局在乱流が準秩序的で大規模なパターンを形成するという研究報告が背景にあります．この層流－乱流パターンの捕捉が，臨界レイノルズ数の決定に重要なのです．図 1 は，圧力勾配駆動の平行平板間チャネル乱流の亜臨界遷移過程で（小職の DNS により初めて）捉えた，

層流－乱流パターンの 3 次元可視化図です，この縞状の局在乱流を乱流縞と名付けました[2-3].

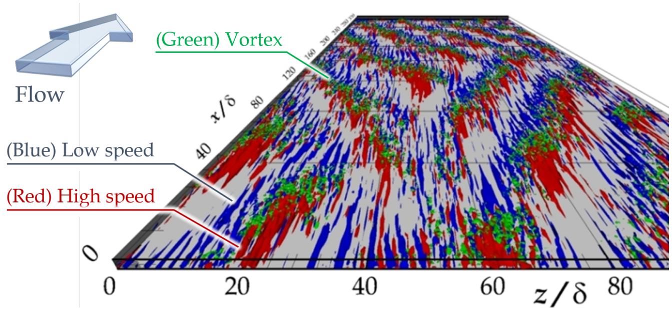

図１　チャネル乱流に現れる乱流縞．δはチャネル半幅．

流路形態に依存する層流―乱流パターン形成について，統一的理解を目指した研究も進めてきました．環状ポアズイユ流の DNS により円管内流（のパフ）と平行平板間流（の乱流縞）の接続を試み[4-5]，環状クエット流の解析では有向パーコレーションの特徴を持つ非定常で確率的な局在乱流現象を見出すことに成功しました[6]．乱流縞のロバスト性に関する解析も行い，粗面上では主流に垂直な乱流帯が形成されることを発見しました[7-8]．現在は，乱流摩擦抵抗低減効果をもたらす粘弾性流体を対象に，乱流縞のロバスト性や特異な遷移過程（弾性乱流）に関心を持っており，その調査に向けて JSPS 特別研究員 PD 河田卓也博士と同 DC1 仁村友洋君に協力を得ながら DNS 基礎研究を進めております[9-10].

上記テーマの他に，研究室では 4 つのメインテーマが走っています．1) 粘弾性流体乱流の DNS（図 2）と乱流モデル構築，2) 冠動脈ステントによる血流影響評価，3) 界面張力駆動の液滴・気泡操作の CFD，4) 乱流ビッグデータの機械学習，の 4 つでいずれも CFD シミュレーションが絡みます．将来，これらの成果も是非ご紹介したいものですが，再びこの度のような機会を頂くよう精一杯，研究に励んで参ります．変わらぬご指導ご鞭撻のほど，宜しくお願い申し上げます．

末筆ながら，河村洋先生の他，川口靖夫教授（東京理科大学），河原源太教授（大阪大学）をはじめ多くの先生方に乱流遷移研究の遂行において常に温かい励ましを頂きましたこと，深くお礼を申し上げます．環状流の DNS は石田貴大博士（現・JAXA）が主体的に行い，その他の研究においても指導した卒研生・院生の貢献が無ければ実現しないものばかりでした．これからも乱流は勿論，計算力学・CFD の魅力と技術を後世に伝えつつ，わずかでも学界・社会に寄与できるよう益々精進する所存です．

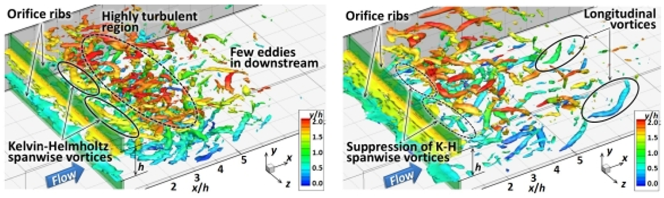

図２　２次元スリット・オリフィスを過ぎるチャネル乱流の DNS．オリフィス直後の渦を可視化．（左）ニュートン流体，（右）同レイノルズ数の粘弾性流体では，渦が抑制される．

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