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特集：令和4年度　日本機械学会　材料力学部門賞　受賞者の言葉

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Japan Society of Mechanical Engineers Mechanics of Materials Division Award Winner's Words

業績賞：接着・接合・締結における強度設計に関する一連の先駆的研究

Achievement Award: A Series of Pioneering Research on Strength Design in Adhesion, Joining, and Fastening

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この度は，日本機械学会材料力学部門業績賞という栄えある賞を頂き，誠に光栄に存じます．ご推薦頂いた先生方をはじめ，選考等でお世話になりました多数の諸先生方に心から御礼申し上げます．今回の業績は研究室メンバーの協力だけでなく，企業や外部機関との共同研究も含まれます．本稿では，これまで行ってきた研究を振り返り，これまでご指導頂いた先生方，ならびにご協力いただきました関係各位の皆様への感謝も含め，受賞の言葉とさせていただきます．

It is a great honor for me to receive the prestigious Materials & Mechanics Achievement Award of the Japan Society of Mechanical Engineers. I would like to express my heartfelt gratitude to the professors who recommended me, as well as the many other professors who helped me during the selection process. This achievement includes not only the cooperation of laboratory members, but also joint research with companies and external institutions. In this paper, I would like to review the research that I have conducted so far, and express my gratitude to the professors who have guided me and to all the people who have cooperated with me.

卒業研究(九州工大 1978 年～)と修士課程では，村上敬宜先生の弾性力学の授業が大変に面白かっ

たことから，体積力法による３次元応力集中の解析に取り組みました．前年度までの卒業研究で，回転だ円体空か・ドーナツ状空洞の解析が終わっておりましたので，丸棒円筒面での境界条件を Rankin の解を使って満足させ，円周切欠きをもつ丸棒に拡張しました．なお，ドーナツ状空洞と円周切欠きの応力集中係数は精密な計算では数%以内で一致します(Key Engineering Materials Vols. 183-187 (2000) p.499)．修士課程では円周切欠きを有する丸棒の曲げの解析に取り組みました．体積力法で軸対称問題を解析するにはr, z方向に作用する Ring Force による応力場の解を用いればよいのですが, 軸対称体の曲げ問題ではどのような Ring Force を用いればよいのか？先生のご指導の下，Neuber の Kerbspannungslehre を読むなどして，円周上で大きさが$cos\varphi$または$sin\varphi$で変化するr, θ, z方向の Ring Force を考えました．まず，厳密解のある回転だ円体空かの曲げ問題で，その正しさを確認して，→ドーナツ状空洞，→円周切欠きをもつ丸棒へ発展させました．頂いた研究テーマは大変に魅力的で，応力解析に夢中になりました．

In my graduation research (Kyushu Institute of Technology since 1978) and in my master's course, I was very interested in Professor Yukitaka Murakami's class on Theory of Elasticity, so I worked on the analysis of three-dimensional stress concentration using the body force method. Until the previous year, an ellipsoidal cavity of revolution and a toroidal hole in an infinite body were already analyzed, I extended to analyzing a round bar by using Rankin's solution. Note that the stress concentration factors of the toroidal hole and the circumferential notch agree within several percent in precise calculations (Key Engineering Materials Vols. 183-187 (2000) p.499). In my master's course, I worked on the bending analysis of a round bar with a circumferential notch. In order to analyze an axisymmetric problem under tension by applying the body force method, the stress fields due to the Ring Force acting in the r- and z- directions can be use the fundamental solution. But what can we use for bending problem? Under the guidance of my professor, I read Neuber's Kerbspannungslehre, etc., and found out the Ring Force in the r, θ, and z directions whose magnitude changes with cosφ or sinφ on the circumference. First, the validity of those fundamental solutions was confirmed in bending an ellipsoidal cavity since the exact solution is available, and developed it into →a toroidal hole →a notched round bar. The research theme I received was very attractive, and I was absorbed in stress analysis.

博士課程(九州大学 1981 年～)では西谷弘信先生のご指導で，体積力法による軸対称体の引張り・ねじり・曲げの問題の解析法を明確にしました. 学位論文の骨子は修士の研究で終えていましたが，特異積分の処理方法やプログラミングを改良することで，長谷川久夫先生の解と有効数字 4～5 桁まで一致する結果を得ました．体積力法は１つ１つの問題を工夫して解くことが必要ですが，それによってずいぶん学ぶことも多く，その経験は産学連携研究にも有用であったと思います．西谷弘信先生には，九州工大に赴任後（1984 年～）もご指導を賜り，切欠き試験片に関しては，使用に便利なように切欠き試験片の応力集中係数を誤差 1%以内で与える計算式として与えました（高瀬康博士論文）．研究テーマの決め方に関して，就職後最初に頂いたご助言は，いまでも深く記憶に残っております.

In the PhD course (Kyushu University since 1981), under the guidance of Professor Hironobu Nishitani, I clarified how to apply the body force method to tension, torsion, and bending of axisymmetric bodies. Although an essential part of my dissertation was completed in my master's research, by improving the singular integral evaluation method and programming, I was able to obtain a result that matched Professor Hisao Hasegawa's solution up to 4 to 5 significant digits. In the body force method, it is necessary to devise and solve each problem, but I learned a lot by doing so, and I think that experience was useful for industry-university collaborative research. Professor Hironobu Nishitani provided guidance even after I was assigned to Kyushu Inst. Tech. (1984-). The stress concentration factor of notched specimens is given as a formula within 1% accuracy (Yasushi Takase PhD dissertation). I still remember deeply the advice I received from him when I first started working as a researcher regarding how to decide on a research topic.

早い時期に Fazil Erdogan 先生（Lehigh 大学 1985 年～）の下で研究する機会を頂きました．体積力法と同じ特異積分方程式を，未知関数を基本密度と多項式で近似し，２次元縁き裂を 10 桁以上の精度で解いておられました．それを見て，他の体積力法の方程式も厳密に解きたいと思うようになり，帰国後，き裂全面の境界条件の満足度を吟味しながら，３次元表面き裂の滑らかな K の分布を求めました（機論 61-586,p.1232）．だ円孔/介在物の干渉問題では，解が収束しない場合がありましたので，どのように解けば収束させることができるかを示しました（松尾忠利博士論文）．この種の研究に関連して，当時，陳玳珩先生が情報工学部におられ，ご相談する機会が戴けたことに感謝しております（小田和広博士論文など）．陳先生は，体積力法の著書だけでなく，異種接合材の特異応力場の解析も多くなされており，それらの理論を参考にして，種々の Butt Joint や Scarf Joint の接着強度が界面端部の特異応力場の強さ＝一定で表現できることや，曲げの影響を受けない，Lap Joint の試験片厚さを示すことができました（李戎・任飛・高木怜博士論文など）.

Early on, I had the opportunity to study under Professor Fazil Erdogan (Lehigh University 1985-). I was impressed his lab used hypersingular integral equations, which is equivalent to the body force method; then, by approximating the unknown body force with fundamental densities and polynomials, the two-dimensional edge crack was solved with an accuracy of 10 orders of magnitude or more. This made me want to rigorously solve the other singular integral equations of the body force method. After going back to Japan, I calculated the exact variation of the stress intensity factors of a semi-elliptical surface crack (Trans JSME 61-586, p.1232).In the elliptical hole/inclusion interference problem, the solution sometimes did not converge, so we showed how to solve it to make it converge (Tadatoshi Matsuo PhD dissertation). In relation to this kind of research, I am grateful to have had the opportunity to consult with Prof. Dai-Heng Chen, who was in the Faculty of Computer Science, Kyushu Inst. Tech. at that time (Kazuhiro Oda's doctoral dissertation, etc.). Dr. DH Chen has not only published books on the body force method, but also analyzed various singular stress fields of dissimilar bonding materials. By utilizing the theory, we were able to show that the adhesive strength of various butt joints and scarf joints can be expressed as a constant value of the ISSF (Intensity of Singular Stress Field), and a desirable specimen geometry of lap joint, which is not affected by bending deformation.

1995 年頃ガスケットの劣化で配管継手から漏れが生じるため，発明されたガスケットレスフランジの相談がありました（機論 66-643, p.966）．それを契機に企業との共同研究を行うようになり，社会人博士も受け入れました（安藤誠人・池田朋弘・日高哲郎・斉藤亮一・斉藤金次郎博士論文）．産学連携の恩人である田中洋征先生のご尽力で，5 件の経済産業省の助成も頂きました．二重ねじのプロジェクトでは，西田新一先生・竹増光家先生・大喜工業㈱との共同研究で，ナットの緩みやボルトの疲労強度を考える機会を頂きました．その後，単一のナットとボルトに適切なピッチ差を与えることで，緩み止めと強度向上が実現できることを示しました（陳鑫・劉渓・王彪博士論文など）．

Around 1995, there was a consultation about the invented gasketless flange because deterioration of gaskets caused leakage from piping joints (Trans JSME 66-643, p.966). Taking this opportunity, we began to conduct joint research with companies, and accepted working doctorates (Masato Ando, Tomohiro Ikeda, Tetsuro Hidaka, Ryoichi Saito, and Kinjiro Saito, PhD dissertations). Thanks to the efforts of Prof. Hiroyuki Tanaka, who is a benefactor of industry-academia collaboration, we also received five subsidies from the Ministry of Economy, Trade and Industry. In the double screw project, I had the opportunity to consider the loosening of nuts and the fatigue strength of bolts through joint research with Professor Shinichi Nishida, Professor Teruie Takemasu, and Daiki Kogyo Co., Ltd. After that, it was shown that by giving an appropriate pitch difference to a single nut and bolt, it is possible to prevent loosening and improve strength (Xin Chen, Xi Liu, Biao Wang PhD dissertations).

日立金属㈱との共同研究では，まず，連続溶融亜鉛めっきラインに使用する，セラミック製ロールの開発を始めました．従前のステンレス製ロールでは，通常 2 週間程度でラインを停止しロール交換等を行います．溶融金属への浸漬時の熱応力・稼働中の応力・接合部の解体の解析などによって，開発に貢献しました（Hendra・栗文彬博士論文）．このようなセラミック製ロールには焼嵌め接合が不可欠と判明しましたが，一方で，稼働中に軸が抜け出しました．この現象は，抜け出し方向に外力がない条件下で生じる新しい損傷でしたので，ロール回転を荷重の移動で表現する荷重移動法によって，抜け出し現象を数値実験で模擬しました．その結果，接合部に不可逆的変形が生じ，その変位が蓄積して軸抜けが生じるメカニズムを明らにしました（Dedi・張国偉博士論文）．

In joint research with Hitachi Metals, Ltd., we first started developing ceramic rolls for use in continuous hot-dip galvanizing lines. With conventional stainless steel rolls, the line is usually stopped in about two weeks and the rolls are replaced. Contributed to the development by analysis of thermal stress during immersion in molten metal, stress during operation, dismantling of joints, etc. (Hendra and Wenbin Li PhD dissertation). Shrink-fitting was found to be essential for such ceramic rolls, but on the other hand, the shaft slipped out during operation. This phenomenon was a new type of damage that occurred under the condition that there was no external force in the pull-out direction. As a result, irreversible deformation occurs in the joint, and the mechanism of the accumulation of the displacement causing the axis to come off was clarified (Dedi and Guowei Zhang, PhD dissertations).

圧延用ロールに関しては，ロールメーカー2 社との共同研究により，熱処理と残留応力の関係を調べました．実態に即してクリープ変形も解析に取り入れました．これらの研究では，ロールの権威の佐野義一博士から，勤務先の日立金属㈱を退社後は大学の支援研究員としても，多大のご指導を賜りました．一例として，通常のロール全体を均一に加熱した後の焼入れと比べて，ロール内部

が表面温度以下の状態で焼入れする，不均一加熱焼入れ法が有用であり，ロール中心の引張残留応力と内部破損リスクを低減できることを示しました（胡可軍博士論文）．残留応力を初期条件として，圧延時の応力も初めて解析的に考察し，遠心鋳造製複合ロールの HSS/DCI 境界の危険部位を明らかにし，ロールの疲労強度を評価しました（Radzi 博士論文）．

Regarding rolling rolls, we investigated the relationship between heat treatment and residual stress through joint research with two roll manufacturers. In line with the actual situation, creep deformation was also incorporated into the analysis. In these studies, I received great guidance from Dr. Yoshikazu Sano, an authority on rolls, even as a research academic fellow at a Kyushu Institute of Technology after leaving Hitachi Metals, Ltd., where he worked. As an example, a non-uniform heat quenching method, in which the inside of the roll is quenched at a temperature below the surface temperature, was found to be useful compared to the normal quenching after uniformly heating the entire roll. This is because the failure risk at the roll center risk can be reduced by providing smaller tensile residual stress (Hu Kejun PhD dissertation). Using the residual stress as the initial condition, we analyzed the stress during rolling for the first time, clarifying the critical regions at the HSS/DCI boundary of the centrifugally cast bimetallic roll, and evaluated the fatigue strength of the roll (Radzi PhD dissertation).

ところで，圧延用ロールにおいても，その構造をスリーブ組立式に移行する考え方があり，コスト縮減だけでなく，現状のロールの限界を超えた要求を満たす候補とされています．一方で，圧延中にスリーブが滑らないように設計されていても，スリーブが周方向にすべる現象が存在し，従来の設計基準（駆動トルク＜摩擦抵抗トルク）では説明不可能です．よって，荷重移動による数値実験でこれを実証し，ミニチュアロールによる模擬実験では．スリーブ内面に損傷が生じる過程を明らかにしました（酒井悠正・Rahimah 博士論文）．特に，自由転がり条件下（駆動トルク 0）でも界面すべりを解析と実験で確認しましたので，今後転がり軸受けの界面クリープ問題（類似の現象）への応用が期待できます．界面すべりは，荷重負荷により不可逆的すべり変形が局所的に生じ，ロール回転（すなわち荷重移動）時に，それらが蓄積されていくことで生じます．駆動トルクによってすべり量は増大し，圧延トラブルの際には，特に大きなすべりが生じます．これは不可逆的すべりが生じる領域が駆動トルクにより拡大することからも説明できます．

There is an idea to shift the structure of rolling rolls to the sleeve assembly type, and it is considered a candidate that not only reduces costs but also satisfies the requirements beyond the limits of the current rolls. On the other hand, even if the sleeve is designed so that it does not slip during rolling, there is a phenomenon in which the sleeve slips in the circumferential direction, which cannot be explained by the conventional design criteria (driving torque < frictional resistance torque). Therefore, this is verified by numerical experiments using load shifting method, and simulated experiments using miniature rolls. We clarified the process of damage on the inner surface of the sleeve (Hiromasa Sakai and Rahimah PhD dissertation). In particular, we confirmed the interfacial slip even under free rolling conditions (driving torque 0) by analysis and experiment, so it is expected to be applied to the interfacial creep problem (similar phenomenon) of rolling bearings in the future. Interfacial slip occurs when irreversible slip deformation locally occurs due to loading and accumulates during roll rotation (that is, load shifting). The amount of slip increases with drive torque, and a particularly large amount of slip occurs during rolling troubles. This can also be explained by the expansion of the region where irreversible slip occurs due to the drive torque.

学会は機械学会の材料力学分野を中心としてきました．接着問題を始めたのは古口日出男先生とのお話しが契機でしたし，上田整先生のご質問で計算の誤りに気付いたことなど，多くの思い出がございます．ご指導いただきました材料力学部門の先生方に深くお礼申し上げますとともに，部門の益々の発展をお祈り致します．

Participation in academic societies has centered on the field of mechanics of materials of the Japan Society of Mechanical Engineers. I have a lot of memories, such as the discussion with Professor Hideo Koguchi that started the adhesive problem, and the fact that I realized an error in the calculation by Professor Sei Ueda's question. I would like to express my deep gratitude to the professors of the Division of Materials & Mechanics for their guidance, and I wish the Division's further development.