Delightful Petra, Delighted World

DEACE

DIGITAL & EMPATHIC
ARCHITECTURE CIVIL ENGINEERING
INTERNATIONAL CONFERENCE

BOOK OF ABSTRACT

20-21
AUGUST
2021

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FOREWORD

Dear Colleagues,

Dear Friends,

On behalf of the organizing committee, we would like to extend our warmest welcome to you to the Digital & Empathic Architecture & Civil Engineering (DEACE) International Conference.

DEACE International Conference and International Student Workshop on Bamboo Gridshell Computational Design are Virtual Events being held by the Faculty of Civil Engineering & Planning as a series of events celebrating the 60th Anniversary Petra Christian University, "The Rock Turns Diamond!"

DEACE aims to gather researchers, scholars, and practitioners all over the world to share and exchange their knowledge and breakthrough in the fields of Architecture and Civil Engineering especially toward the new era.

We would like to thank all keynote speakers, workshop speakers, scientific committee, session chairs, authors/presenters, participants, sponsors, conference & workshop coordinators, and everybody who has all contributed to this conference with great efforts for months.

We do hope that you enjoy your attendance at the DEACE 2021!

Dr. Rudy Setiawan

Chair of Organizing Committee DEACE 2021

KEYNOTES SPEAKERS

Prof. Dr. Djwantoro Hardjito
Petra Christian University

Prof. Djwantoro Hardjito is currently a professor at the Civil Engineering Department, Petra Christian University, Surabaya, Indonesia. Concurrently, he is also the rector of the university since 2017. Prior to joining Petra, he was affiliated with Curtin University, Malaysia, for five years until 2009. He was the recipient of Australian Development Scholarship Award to pursue his doctoral degree at Curtin University, Australia, and Japan-ADB Scholarship Award for his Master's degree at Asian Institute of Technology, Thailand. His research interest is in the area of geopolymer concrete and the use of waste as construction materials. He has published more than 50 scientific articles in international journals and conference proceedings. He has received several invitations to deliver keynote speeches in international conferences.

Prof. Andrew Charleson
Victoria University of Wellington, New Zealand

Andrew Charleson has recently retired as an Associate Professor, School of Architecture, Victoria University of Wellington, New Zealand. He has taught the subject of architectural structures in lecture and studio settings for over 30 years. During this time, he has won several teaching awards, including a National Tertiary Teaching Excellence Award for Excellence in Innovation.

Andrew has two main strands of research interest. The first strand, how structure can enrich architecture, was brought together in the book Structure as Architecture: a Source Book for Architects and Structural Engineers. The first edition was published by Elsevier in 2005, and the second by Routledge in 2014. Andrew is currently working with a landscape architect on another book, Structures in the Landscape.

The second research strand relates to earthquake engineering. In 2008 his book Seismic Design for Architects: Outwitting the Quake was published by Elsevier, and he is the co-author of Seismic Isolation for Architects, published by Routledge in 2016.

In his retirement, Andrew is a voluntary visiting professor in schools of architecture. So far, he has visited universities in Indonesia, Albania, Croatia and Serbia.

Back in the early 1980's Andrew and his family lived in Bandung for over two years. Andrew was part of a bi-lateral aid project to introduce Indonesia's first seismic code. He worked in the DPMB, now called PUSKIM.

Prof. Dr. Janice Rieger

Queensland University of Technology,
Australia

Dr Janice Rieger is a Senior Lecturer in the School of Design, Creative Industries Faculty at QUT, Australia. She has sixteen years of international post-secondary teaching experience, over five years in museum and gallery studies and fifteen years of experience in design. Her research in history, theory and criticism looks at the relationship between disability, design and material culture from a spatial perspective. Janice is a Chief Investigator with the Centre for Justice and the Design Lab at QUT. She is also the QUT Research Ethics Advisor at the School, Faculty and University Level and a Senior Fellow with the Higher Education Academy, UK. Dr Rieger has served as a faculty member at the University of Calgary, (Calgary, Canada), York University (Toronto, Canada), Mount Royal University (Calgary, Canada), and the University of Alberta (Edmonton, Canada). She has been a visiting scholar at the University of Hasselt (Hasselt, Belgium) and L'Université Catholique de Lille (Lille, France). From her advocacy with people with disabilities, she was awarded a Mayor's Award, Government of Alberta State-wide Award and was recently invited to be the first overseas member of the European Institute for Design and Disability. In Canada, she co-founded a national certificate program in accessible housing design (CSAHD). Her work in inclusive design has led to code, policy, curriculum and legislative changes in Australia, North America and Europe. Dr Rieger is on the editorial board for the European Society for Disability Research (ALTER, Elsevier), and co-facilitated the 2018 International Disability Mundus doctoral school in France. Dr Rieger is also on the Scientific Advisory Board for Applied Human Factors and Ergonomics (AFHE), USA. Her research focuses on creating cultures of inclusion and her recent publications were featured in The Routledge Handbook of Disability Arts, Culture and Media (2019), Space and Culture (2019) and CoDesign - International Journal of CoCreation in Design and the Arts (2019).

Prof. I-Tung Yang, Ph.D.

National Taiwan University of Science and Technology, Taiwan

Professor I-Tung Yang obtained his Ph.D. in Civil and Environmental Engineering from The University of Michigan, Ann Arbor in 2002. Previously, he held a master's degree in industrial and Operations Engineering and Construction Engineering and Management from the same institute.Professor I-Tung Yang specialties in Construction Management, Computational Intelligence, Decision-making and Risk Analysis, and Information Technology has brought him to be the Chair, Department of Civil and Construction Engineering at the National Taiwan University of Science and Technology from 2018 up to the present, as well as Professor in Department of Civil and Construction Engineering Specialty. He has also been the president of Taiwan Construction Research Institute from 2015-2018.Professor I-Tung Yang also contributes to larger scaled education development, by becoming an associate editor in KSCE Journal of Civil Engineering, Grant Proposal Review Board, Ministry of Science and Technology, Taiwan, Co-investigator, National Energy Program, Taiwan, and become a member of the review board in many international journals. He is also a member of the International Science Committee in the International Symposium on Reliability Engineering and Risk Management.He is also the chair of Chinese Taipei APEC Engineer/IntPE Monitoring Committee, Information Technology Committee, Chinese Institute of Civil Hydraulic Engineering, Disaster Mitigation Committee - Chinese Institute of Engineers, and member board and committee in many civil engineering institutes.

Dr. Wen-Shao Chang

University of Sheffield, UK

Dr. Wen-Shao Chang joined the Sheffield School of Architecture in 2017, and he is now Director of Postgraduate Research Programme. Prior to joining SSoA, he worked for the Kyoto University, Japan, as a JSPS Fellow and the University of Bath as a lecturer. He has a dual background in Architecture and Structural Engineering, and hold the degrees of BS Arch, MS Arch and PhD from National Cheng Kung University, Taiwan. His research interest is in exploring natural materials utilisation and strategies to achieve low impact in buildings. In SSoA, he is part of People, Environment and Performance (PEP) research group. His full biography can be seen on the SSoA website: https://www.sheffield.ac.uk/architecture/people/academic-staff/wen-shao-chang

Esti A.Nurdiah, Ph.D. (cand)

Petra Christian University, Indonesia

Esti Nurdiah is a lecturer at the Department of Architecture, Petra Christian University, Surabaya, Indonesia. She was graduated from Universitas Gadjah Mada and completed her master degree at Institut Teknologi Sepuluh November, Indonesia. Currently, Esti is studying at Sheffield School of Architecture for her PhD in Architecture, and for her study, she is sponsored by Indonesia Endowment Fund for Education (LPDP). Through her research, she aims to explore the utilisation of bamboo for gridshell structure by analysing the material, structural morphology, forces and construction methods.

Wong Foek Tjong, Ph.D.

Petra Christian University, Indonesia

Dr. Wong Foek Tjong is currently an associate professor at the Department of Civil Engineering, Petra Christian University, Surabaya. He received his Ph.D. degree from Asian Institute of Technology, Thailand in 2009. His research interests include developments and applications of finite element methods for static, dynamic, and stability analyses of structures, and structural optimizations. He has published tens of scientific articles in international journals and conference proceedings. (ID Scopus 26530527000, Google ID nCVRs_4AAAAJ). Email wftjong@petra.ac.id

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SCHEDULES

Schedule Conference Day 1 – August 20th, 2021

Keynote Session	07:30-08:00		Participants enter the zoom meeting Link : https://petra.id/DEACE-DAY1 Passcode : DEACE2021
	08:00-08:10		**Conference Opening –** Greetings and Prayer
	08:10-08:20		**Welcoming Speech from Organizing Committee Chairman and The Dean of The Faculty of Civil Engineering and Planning** *Dr. Rudy Setiawan*
	08:20-08:30		Profile Video of The Faculty of Civil Engineering and Planning + Conference Day 1 Photo Session
	08:30-09:45		**Keynote Session I** - *Prof. Dr. Djwantoro Hardjito* (08.30 – 09.15 : Presentation → 09.15 – 09.45: Q&A Session)
	09:45-10:00		**Sponsor Session** -
	10:00-10:15		Break
	10:15-11:30		**Keynote Session II** - *Prof. Andrew Charleson* (10.15 – 11.00 : Presentation → 11.00 – 11.30: Q&A Session)
	11:30-12:45		Lunch Break
Parallel Session	12:45-13:00	Zoom General Room	Participants enter the zoom meeting Link : https://petra.id/DEACE-DAY1 Passcode : DEACE2021 *Please change your username so we can move you to the correct breakout room*
	13.00-15.00	Breakout Room 1	**Parallel Session 1** **Civil Engineering Paper** (details on p.15) Sub-theme: Structural Engineering and Materials
		Breakout Room 2	**Parallel Session 1** **Architectural Paper** (details on p.16) Sub-theme: Building Science and Technology
	15.00-15:15		Back to Zoom general room, break Please change your username so we can move you to the correct breakout room
	15.15-17.15	Breakout Room 1	**Parallel Session 2** **Civil Engineering Paper** (details on p.17) Sub-theme: Construction Management
		Breakout Room 2	**Parallel Session 2** **Architectural Paper** (details on p.18) Sub-theme: Architecture and Urban Development
	17.15		The first day of the conference is over

Schedule Conference Day 2 – August 21st, 2021

Parallel Session	07:30 - 08:00	Zoom General Room	Participants enter the zoom meeting Link : https://petra.id/DEACE-DAY2 Passcode : DEACE2021
	08.00 – 09.15	Prayer **Keynote Session III** – *Prof. I Tung Yang, Ph.D.* (08.00 – 08.45 : Presentation → 08.45 – 09.15: Q&A Session)	
	09.15 – 09.30	**Sponsor Session –** Assign to breakout room	
	09.30 - 11.30	Breakout Room 1	**Parallel Session 3** **Civil Engineering Paper** (details on p.19) Sub-theme: Structural Engineering and Materials
		Breakout Room 2	**Parallel Session 3** **DEACE Student Workshop Presentation** (details on p.20)
	11.30 – 12.30	Break, All participants back to zoom general room	
	12.30 – 14.30	Breakout Room 1	**Parallel Session 4** **Civil Engineering Paper** (details on p.21) Sub-theme: Transportation
		Breakout Room 2	**Parallel Session 4** **DEACE Student Workshop Presentation** (details on p.20)
Keynote Session	14.30 – 14.45	Break, All participants back to zoom general room Link : https://petra.id/DEACE-DAY2 Passcode : DEACE2021	
	14:45 – 16.00	**Keynote Session IV** – *Prof. Dr. Janice Rieger* (14.45 – 15.30 : Presentation → 15.30 – 16.00: Q&A Session)	
	16.00 – 16.30	**Closing Session** The announcement of Best Paper and Best Workshop Design Conference Photo day 2 – Winners Photo group Closing Remarks	

Parallel Session 1 – Breakout Room 1

BR 1 - Civil Engineering		Moderator	Wong Foek Tjong, Ph.D.	
		Subtheme	Structural Engineering and Materials (A1)	
Date	**Time**	**Paper ID**	**Title**	**Author**
20 August 2021	12.45 - 13.00	Registration		
	13.00 - 13.20	A1-1	A Comparative Study of Several Bio-Inspired Algorithms in Cost Optimization of Cellular Beams	Ansheilla Tjahjono, Evelyn Jane Wijayanti, Doddy Prayogo, Wong Foek Tjong
	13.20 - 13.40	A1-2	The Study of Shear Wall Use in Buildings during the Architecture Design Process	Livian Teddy, Husnul Hidayat, Dessa Andriyali A.
	13.40–14.00	A1-3	Modified Partial Capacity Design (M-PCD) Method	Levin Sergio Tanaya, Herryanto, Pamuda Pudjisuryadi
	14.00 - 14.20	A1-4	Comparison Reinforcement Design Shear Wall Modelling Planar and Assembly in Elevator Shaft	Daud Rahmat Wiyono, Roi Milyardi, Yosafat Aji Pranata, Anang Kristianto
	14.20 - 14.40	A1-5	A Comparative Study of Several Nature-Inspired Algorithms in Steel Deck Floor System Cost Optimization	Timothy Emanuel, Hadrian, Doddy Prayogo, Wong Foek Tjong
	14.40 - 15.00	A1-6	Review of Autonomous Self-Healing Cementitious Material	Sofian Arif Susanto, Antoni, Djwantoro Hardjito
	15.00	Back to main room, short break, preparation to the next parallel session 2		

- **Time for each paper includes the Q&A session**
- **Please follow this name format**
  - ✓ For Presenters : PAPER ID_Presenter name
  - ✓ For Participants : Participant_Your name

Parallel Session 1 – Breakout Room 2

<table>
<tr><th colspan="2" rowspan="2">BR 2 - Architecture</th><th>Moderator</th><th colspan="2">Prof. Lilianny Sigit Arifin, Ph.D.</th></tr>
<tr><th>Subtheme</th><th colspan="2">Building Science and technology (B1)</th></tr>
<tr><th>Date</th><th>Time</th><th>Paper ID</th><th>Title</th><th>Author</th></tr>
<tr><td rowspan="8">20 August 2021</td><td>12.45 - 13.00</td><td colspan="3">Registration</td></tr>
<tr><td>13.00 - 13.20</td><td>B1-1</td><td>Designing louvers toward optimum daylight performance in Indonesia: A parametric study</td><td>Rendy Perdana Khidmat, Hiroatsu Fukuda, Kustiani, Andi Prasetiyo Wibowo</td></tr>
<tr><td>13.20 - 13.40</td><td>B1-2</td><td>The Importance of Iterative Process in Façade Design Optimization for a Green Office Building in South Tangerang City</td><td>Dian Fitria</td></tr>
<tr><td>13.40–14.00</td><td>B1-3</td><td>Comparison of Shibataea kumasasa and Equisetum hyemale as vertical greenery system for thermal and light shade in student's architectural design studio in Surabaya</td><td>Luciana Kristanto, Wanda W.Canadarma, Elvina S.Wijaya</td></tr>
<tr><td>14.00 - 14.20</td><td>B1-4</td><td>Experimental study on ventilation using earth-to-air heat exchange in Surabaya</td><td>Anik Juniwati, Danny Santoso Mintorogo, Azarya Ezra Abednego, Stevie Kurnoawan, Eka Dewi Handoyo</td></tr>
<tr><td>14.20 - 14.40</td><td>B1-5</td><td>Comparison of simulation-based methods and metaheuristic optimization algorithms for optimizing window design by considering daylighting and heat transfer in tropical region of Indonesia</td><td>Aris Budhiyanto, Adrianto Oktavianus, Belinda Tedjokusumo, Kevin Harsono, I-Tung Yang</td></tr>
<tr><td>14.40 – 15.00</td><td></td><td></td><td></td></tr>
<tr><td>15.00</td><td colspan="3">Back to main room, short break, preparation to the next parallel session 2</td></tr>
</table>

- **Time for each paper includes the Q&A session**
- **Please follow this name format**
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Parallel Session 2 – Breakout Room 1

BR 1 - Civil Engineering		Moderator	Doddy Prayogo, Ph.D.	
		Subtheme	Construction Management (C)	
Date	**Time**	**Paper ID**	**Title**	**Author**
20 August 2021	15.00-15.15	Registration		
	15.15-15.35	C-1	Empowering Female Students to be Successful Professionals in the Construction Industry	Christina Liem, Riza Yosia Sunindjio, Cynthia Wang
	15.35-15.55	C-2	Intellectual Intelligence and Emotional Intelligence of Project Manager	Gregorio Reinaldo, Andi, Vincent Ong.
	15.55-16.15	C-3	Causes of Work Accidents and its Impact on the Road and Bridge Construction Projects	Josefine Ernestine Latupeirissa, Irwan Lie Keng Wong, Herby Calvin Paskal Tiyow
	16.15-16.35	C-4	Lean Construction and Project Performance in the Australian Construction Industry	Muhammad Fauzan, Riza Yosia Sunindijo
	16.35 -16.55	C-5	Actual and Expected Transactional and Transformational Leadership Behaviors of Project Managers	Andi, Kevin Sugianto, Arsenius Felix Khoesasih
	16.55 – 17.15	C-6	A preliminary survey on the understanding and application of digital and emphatic engagement of the construction constituents in Surabaya	Paulus Nugraha , M Jonathan , A Listio .
	17.15	The first day of the conference is over		

- **Time for each paper includes the Q&A session**
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Parallel Session 2 – Breakout Room 2

BR 2 - Architecture		Moderator	Timoticin Kwanda, Ph.D.		
		Subtheme	Architecture and Urban Development (B2)		
Date	**Time**	**Paper ID**	**Title**		**Author**
20 August 2021	15.00-15.15	Registration			
	15.15-15.35	B2-1	The Uniformity Concept of Urban Design: Impact of Cultural Traditions on the Meaning of Balinese Town		Eka Diana Mahira, Bambang Soemardiono, Eko Budi Santoso
	15.35-15.55	B2-2	Reinterpreting local wisdom of Rumah Kaki Seribu as sustainable architecture		Livia Hariyanto, Bagas Cahya Prabaswara, Lilianny Sigit Arifin
	15.55-16.15	B2-3	An investigation into the effectiveness of student-led experiential learning for UG architects and the implications of incorporating AR into such pedagogical exercises.		Matthew Wallwork, Mia Tedjosaputro, Weishun Xu
	16.15-16.35	B2-4	A Study of Place Senses in Museum Online-visits		Rully Damayanti, Bramasta Putra Redyantanu, Florian Kossak
	16.35 -16.55				
	16.55 – 17.15				
	17.15	The first day of the conference is over			

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Parallel Session 3 – Breakout Room 1

BR 1 - Civil Engineering		Moderator	Hartanto Wibowo, Ph.D.	
		Subtheme	Structural Engineering and Materials (A2)	
Date	**Time**	**Paper ID**	**Title**	**Author**
21 August 2021	09.15 - 09.30	Registration		
	09.30 - 09.50	A2-1	Alternative Approach in Partial Capacity Design	Herryanto, Levin Sergio Tanaya, Pamuda Pudjisuryadi
	09.50 - 10.10	A2-2	The Effect of Crumb Rubber in Dense Graded and Open Graded Cold Mixture Asphalt	Paravita Sri Wulandari, Daniel Tjandra
	10.10 - 10.30	A2-3	Modeling and Analysis of 3D-Printed Reinforced and Prestressed Concrete Beams	Jimmy Chandra, Hartanto Wibowo, Darwin Wijaya, Fransisca Oktaviani Purnomo, Pamuda Pudjisuryadi, Antoni
	10.30 - 10.50	A2-4	Optimization of Concentrically Braced Steel Frame Structures Based on SNI 1726:2019, SNI 1727:2020, and AISC 341-16	Jonathan Aloysius, Juan Antonio Sumito, Doddy Prayogo, Hasan Santoso
	10.50 - 11.10	A2-5	Investigation of the Material Mixtures and Fiber Addition for 3D Concrete Printing	Antoni, Audi Agraputra, Daniel Teopilus, Axelino Hadi Sunaryo, Malvin Manuel Mulyadi, Pamuda Pudjisuryadi, Jimmy Chandra, Djwantoro Hardjito
	11.10 - 11.30			
	11.30 –12.30	Break, All participants back to zoom general room		

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Parallel Session 3 – Breakout Room 2

BR 1 - Architecture		Moderator	Rully Damayanti, Ph.D.
		Subtheme	Bamboo Gridshell Computational Design (E)
Date	Time	Presenter	Reviewer
21 August 2021	09.15 - 09.30	Registration	
	09.30 – 10.00	Group 1A	Group 3B
	10.00 - 10.30	Group 2A	Group 1B
	10.30 – 11.00	Group 3A	Group 2B
	11.00 - 11.30	General overview from Lecturers	
	11.30 –12.30	Break, All participants back to zoom general room	

Parallel Session 4 – Breakout Room 2

BR 1 - Architecture		Moderator	Rully Damayanti, Ph.D.
		Subtheme	Bamboo Gridshell Computational Design (E)
Date	Time	Presenter	Reviewer
21 August 2021	12.15 - 12.30	Registration	
	12.30 – 13.00	Group 1B	Group 3A
	13.00 – 13.30	Group 2B	Group 1A
	13.30 – 14.00	Group 3B	Group 2A
	14.00 - 14.30	General overview from Lecturers	
	14.30 –14.45	Break, All participants back to zoom general room	

Please follow this name format

- For Workshop Group : E_Group code_Your name
- For Workshop Audience : Participant_Your name

Parallel Session 4 – Breakout Room 1

BR 1 - Civil Engineering		Moderator	Kardi Teknomo, Ph.D.	
		Subtheme	Transportation (D)	
Date	**Time**	**Paper ID**	**Title**	**Author**
21 August 2021	11.30 - 12.30	Registration		
	12.30 - 12.50	D-1	Changes in Drivers' Viewing Frequency, Maneuver Duration, and Degree of Difficulty During Back-in Parking Maneuver with Different Conditions of Parking Spaces	Rudy Setiawan, Arcelina Saputri Dammara, Billy Cahyadi, Bryan Widarno, Fillbert Hanselly Njoko, Maria Noviani
	12.50 - 13.10	D-2	Sustainable Road-Kill Mitigation in Gladak Perak Bridge at Lumajang, Indonesia	Paravita Sri Wulandari, Hansen Richardo Lestyana, Johnson, Jason F. Tranggono
	13.10 - 13.30	D-3	Probability of Willingness to Pay Road Pricing Based on the Perspective of Households in Jakarta	Melchior Bria, Ludfi Djakfar, Achmad Wicaksono
	13.30 - 13.50	D-4	Potential Damage to Residential Building due to Adjacent Surcharge Fill Loading – Case Studies in Surabaya - Indonesia	Daniel Tjandra, Handoko Sugiharto, Januar Buntoro, Paravita Sri Wulandari
	13.50 – 14.10			
	14.10 - 14.30			
	14.30 –14.45	Break, All participants back to zoom general room		

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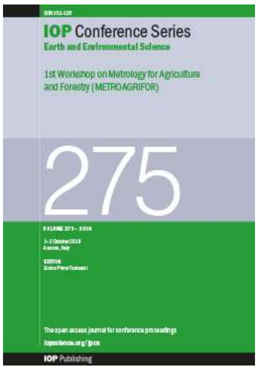
  - ✓ For Participants : Participant_Your name



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Digital and Empathic Engagement in the New Era for Architecture and Civil Engineering 20-21 August 2021, Surabaya, Indonesia

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Open all abstracts

Preface

Structural Engineering and Materials

Building Science and Technology

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Modeling and analysis of 3D-printed reinforced and prestressed concrete beams

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Abstract. Three-dimensional (3D)-printed concrete is believed to have a significant impact in the construction industry in the future. Some research has been conducted experimentally and analytically to investigate the structural behavior of 3D-printed concrete elements, such as beams. Previous study by the authors attempted to analytically model 3D-printed reinforced concrete (RC) beams failing in flexure that were tested by other researchers. The study was done with the aid of a finite element software. However, there are some limitations of the analytical model to simulate the failure mode of the specimens. In this study, an improvement of the analytical model is proposed in order to simulate the behavior of the 3D-printed RC beams more accurately. Furthermore, the analysis was also expanded for 3D-printed prestressed concrete (PC) beam. From the analysis results, it can be concluded that the improved analytical model is able to predict more accurately the failure mode as well as the hysteretic behavior of the 3D-printed RC beams. Nevertheless, a more sophisticated analytical model is needed to improve the accuracy of the prediction for the 3D-printed PC beam.

1. Introduction

Recently, three-dimensional (3D) printing method in the form of additive manufacturing has been applied in various fields. In the industrial sector, for example, 3D printing technology supports the industry 4.0 concept and it has increased the productivity of the sector due to the possibility to create better products. Moreover, it is more practical and does not rely on manual methods which are known to be slower [1].

Concrete is one of the most popular materials in the construction industry. Beside conventional concrete, 3D printing technology has also been applied in concrete manufacturing [2]. It is believed that in the future, 3D-printed concrete will have a significant impact in the construction industry. This is because the technology allows the creation of various complex geometrical shapes without the use of formworks [3].

Modeling and analysis of 3D-printed concrete members have not been fully explored. So far, there were several studies conducted regarding modeling and analysis of 3D-printed concrete structures [4-6]. In these studies, there were some limitations in modeling the constitutive laws of 3D-printed concrete and the type of elements used to simulate its modes of failure. Hence, some of the analyses did not represent well the real behavior of 3D-printed concrete structures.

This study focuses on improving the analytical model used by the authors in the previous study [6]. In this study, OpenSees computer software [7] developed by the Pacific Earthquake Engineering Research Center (PEER) was used to model some 3D-printed reinforced concrete (RC) and prestressed concrete (PC) beams. The analysis results were then compared with the experimental results in order to verify the accuracy of the model in simulating the behavior of 3D-printed concrete members. The analysis results are presented in terms of force-displacement relationships of the specimens as well as their maximum strengths.

2. Past experimental research on the behavior of 3D-printed RC and PC beams

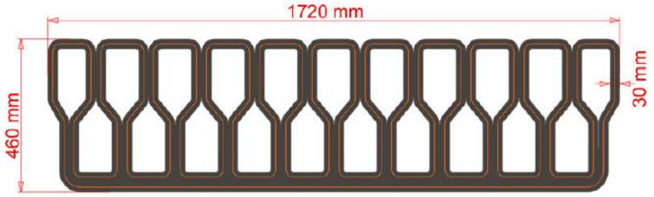
Al-Chaar et al. [8] performed bending tests on nine 3D-printed RC beams to investigate the flexural behavior of these beams since it might differ from the conventional RC beams. The flexural capacity of 3D-printed RC beams might be affected by the interfacial bonding between concrete mortar layers which is limited in 3D-printed concrete. The beams were truss beams with a total length of 4.88 m, 203 mm depth, and 140 mm width. The shear span ratio of the beams was 6.0 or greater. Concrete compressive strength used was 15 MPa and steel rebar yield strength used was 240 MPa. The cross section of the truss beams as well as typical test setup are shown in Figure 1.

(a) (b)

Figure 1. (a) Cross section of typical truss beams and
(b) Aerial view of 3D-printed RC beams tested by Al-Chaar et al. [8].

In this paper, three specimens tested by Al-Chaar et al. [8] were selected to be modeled and analyzed. These specimens are 3DR-S-6B, 4DR-S-0, and 5DR-B-0. Specimen 3DR-S-6B was a doubly-reinforced beam with three 10-mm diameter steel bars each in the tension and compression sides, along with 6 mm basalt mesh. Specimen 4DR-S-0 was similar to specimen 3DR-S-6B, except for the basalt mesh. Specimen 5DR-B-0 was similar to specimen 4DR-S-0, but it used basalt bars instead of steel bars for the tension and compression reinforcement. These specimens were subjected to cyclic loading for both positive and negative directions with an increment of 38 mm in each loading cycle.

Another specimen studied in this paper was a 3D-printed PC beam tested by Salet et al. [9]. They used a half-scale 3D-printed model in order to investigate the structural performance. The specimen cross-section dimensions were 1,720 mm in width and 460 mm in height with concrete compressive strength of 21.5 MPa. The specimen had six segments with a length of 500 mm per segment which were combined together using prestressing tendons with diameter of 15.7 mm and tensile strength of 1860 MPa. There was a total of nine tendons that were stressed with an initial load of 120 kN. The specimen was tested using four-point bending test scheme as shown in Figure 2. The testing protocol was a loading-unloading sequence with an initial load of 120 kN and increment of 30 kN in each cycle.



(a)

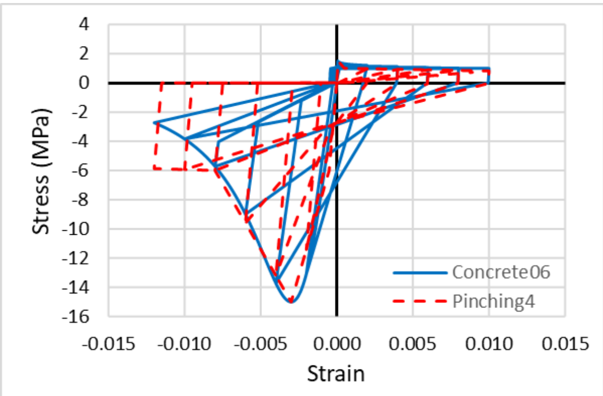
(b)

Figure 2. (a) Cross section of the 3D-printed PC beam and
(b) Four-point bending test setup of the specimen tested by Salet et al. [9].

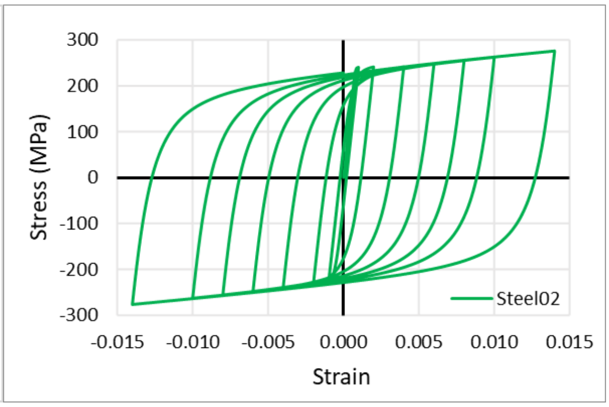
3. Modeling of the 3D-printed RC and PC beams using OpenSees

The type of element chosen to model the 3D-printed RC and PC beams is the Displacement-Based Beam-Column element available in OpenSees [7]. The element was chosen since it could consider the spread of nonlinearity along the element. Furthermore, Truss element was also used in modeling basalt mesh of specimen 3DR-S-6B tested by Al-Chaar et al. [8]. For the element cross-section, Fiber section available in OpenSees [7] was used to model the section of the 3D-printed RC and PC beams.

The basic material used for 3D-printed concrete was Concrete06 that is available in OpenSees [7]. Concrete06 material is originally developed using compressive stress-strain curve proposed by Popovics [10] and tension stress-strain curve developed by Belarbi and Hsu [11]. Later on, after preliminary analysis, the authors decided to slightly modify the unloading-reloading paths of the 3D-printed concrete material using Pinching4 material for the specimens tested by Al-Chaar et al. [8]. This was done to improve the accuracy of the model in predicting the hysteretic behavior of 3D-printed RC beams. A sample of the stress-strain curve of concrete used in this paper is displayed in Figure 3a. To model the rebar, Steel02 material that is available in OpenSees [7] was used. It is based on formulation by Menegotto and Pinto [12] that is generally used to model the constitutive law of steel under cyclic loading. A typical of the stress-strain curve of Steel02 material is displayed in Figure 3b.



(a)



(b)

Figure 3. Typical stress-strain curve of materials used in the analysis: (a) concrete and (b) rebar.

The analyses were carried out using nonlinear static analysis with several load cases to simulate the loading conditions as defined in the experiment by Al-Chaar et al. [8] and Salet et al. [9]. For the PC beam tested by Salet et al. [9], horizontal forces and end moments were preloaded to the beam, in order to take into account the prestressing effect from the tendons. During the analysis, the total applied force and the displacement of the beams were recorded in order to plot the force-displacement curves of the specimens. Subsequently, the curves were compared with those obtained from the experiment by Al-Chaar et al. [8] and Salet et al. [9], in order to evaluate the accuracy of the analytical model in simulating the behavior of 3D-printed RC and PC beams.

4. Analysis results

The analysis results were compared to the experimental results from Al-Chaar et al. [8] and Salet et al. [9] in terms of the force-displacement curves and the maximum strengths of the specimens. The comparison of maximum strengths between experimental and analytical results are presented in Table 1 for all specimens. Furthermore, the comparison of force-displacement curves between experimental and analytical results are presented in Figures 4-7.

Table 1. Comparison of maximum strengths between experimental and analytical results.

Specimen ID	Maximum Experimental Strength (kN)	Maximum Analytical Strength (kN)
	Al-Chaar et al. [8]	
3DR-S-6B	18.207	15.039
4DR-S-0	14.154	13.388
5DR-B-0	7.958	8.159
	Salet et al. [9]	
Prototype	350	308

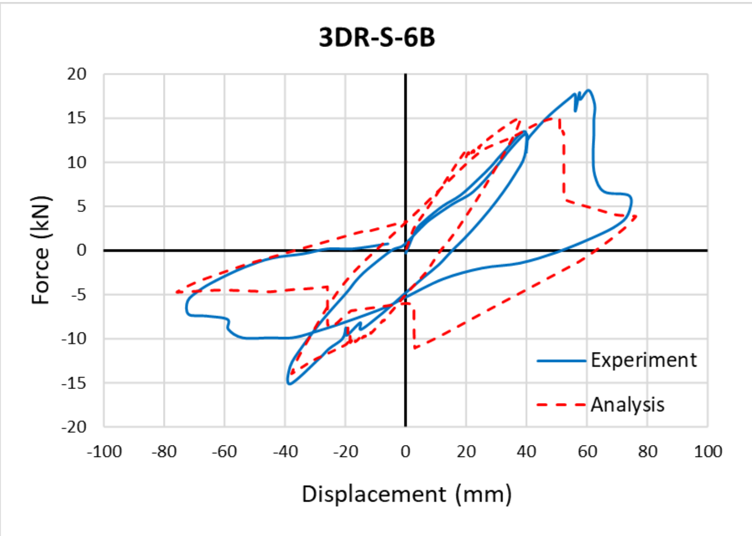


Figure 4. Force-displacement curves of specimen 3DR-S-6B tested by Al-Chaar et al. [8].

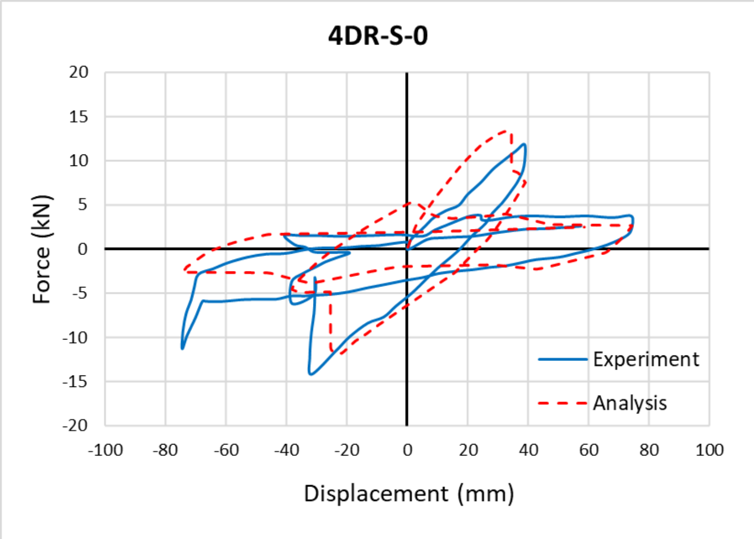


Figure 5. Force-displacement curves of specimen 4DR-S-0 tested by Al-Chaar et al. [8].

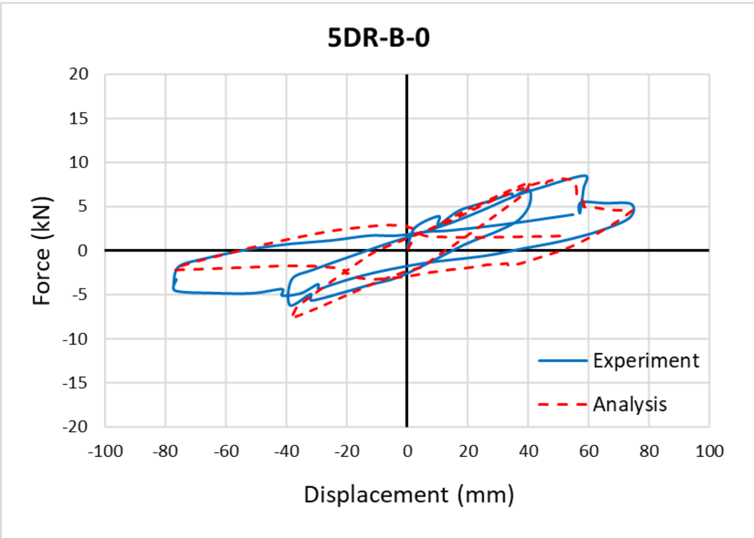


Figure 6. Force-displacement curves of specimen 5DR-B-0 tested by Al-Chaar et al. [8].

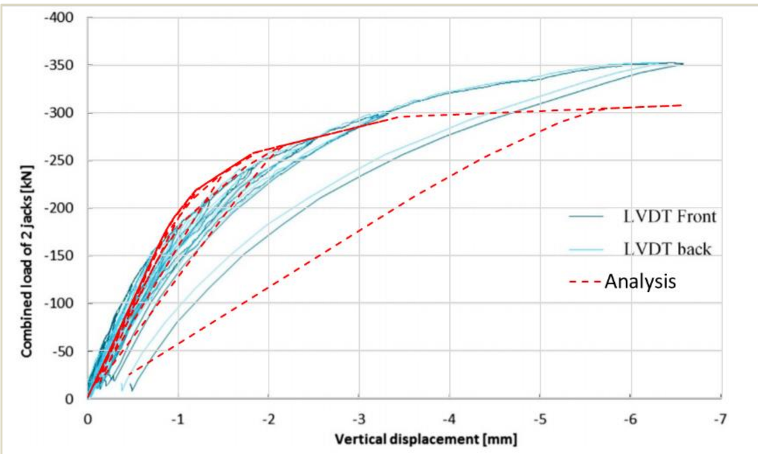


Figure 7. Force-displacement curves of PC beam specimen tested by Salet et al. [9].

The discussions for each specimen are presented herein:

1. Specimen 3DR-S-6B: It can be seen in Figure 4 that the analytical model predicts a higher initial stiffness compared with the experimental result. Furthermore, the analytical model gives almost the same maximum strengths in positive and negative directions whereas the experimental result shows higher maximum strength in positive direction. Thus, the analytical model underestimates the maximum strength of the specimen for about 17.4%. Moreover, it can be seen in Figure 4 that the analytical model can predict the hysteretic behavior of the specimen as well as the mode of failure reasonably well. The failure observed in the experiment was nodal failure which caused the load carrying capacity to drop significantly.
2. Specimen 4DR-S-0: For the force-displacement curve, similar to specimen 3DR-S-6B, it can be seen in Figure 5 that the analytical model predicts a higher initial stiffness compared to the experimental data. The maximum strengths in both directions are similar for the analytical model whereas the experimental result shows higher maximum strength in the negative direction. From Figure 5, it can be seen that the analytical model can predict well the hysteretic behavior of the specimen as well as the failure mode, i.e. nodal failure, including the significant degradation in strength and stiffness. From Table 1, it can be seen that the maximum strength predicted by the analytical model is very close to the experimental strength. It only differs by 5.4%.
3. Specimen 5DR-B-0: It can be seen in Figure 6 that the analytical model can predict the initial stiffness, the hysteretic behavior, and the failure mode of the specimen quite accurately. From Table 1, unlike the two previous specimens, the analytical model slightly overestimates the maximum strength, with a difference of about 2.5%.
4. PC beam specimen: It can be seen in Figure 7 that the analytical model can predict the early-stage behavior of the PC beam specimen quite well. However, starting from the load of 150 kN onwards, the prediction begins to deviate from the experimental result. Ultimately, the analytical model underestimates the peak strength of the specimen by about 12.0%. The difference in the peak strength possibly came from the contribution of prestressing tendons to bending capacity of the 3D-printed PC beam. In the analytical model, the prestressing tendons were not modeled explicitly. Instead, the prestressing forces were applied as horizontal forces and end moments to the beam. Hence, the bending capacity of the analytical model depends only on the prestressing forces as well as the tensile strength of concrete. This is not the case for the actual specimen that had prestressing tendons in the bottom side of the beam that might contribute to its bending capacity. As mentioned by Salet et al. [9], visually noticeable flexural crack was observed at the load of 300 kN. This means from this point forward, the tensile stresses were carried mostly by the prestressing tendons. Therefore, in the testing done by Salet et al. [9], the PC beam specimen could resist a higher load up to 350 kN before the testing was stopped.

5. Conclusions

From the results of this study, some conclusions can be drawn:

- The constitutive law for conventional concrete can adequately be used to model 3D-printed RC and PC beams failing in flexure. In this study, Concrete06 material that was developed based on compressive stress-strain curve proposed by Popovics [10] and tension stress-strain curve developed by Belarbi and Hsu [11] were used to model the 3D-printed concrete. However, some modifications on the unloading-reloading paths were introduced to the material model using Pinching4 material in order to improve the accuracy of the analytical model in predicting the hysteretic behavior of the specimens tested by Al-Chaar et al. [8]. For specimen tested by Salet et al. [9], the original Concrete06 material that is available in OpenSees [7] library was used since the loading of the specimen was done only in one direction.
- Based on the analysis results, the mode of failure of the specimens can be predicted quite accurately by the analytical model. This shows an improvement from the previous study by the authors [6]. In the previous study, the analytical model did not correctly predict the mode of

failure. Nevertheless, in the current analytical model, the maximum strengths predicted were not close enough to the experimental strengths for some specimens.

- The analytical model predicts a higher initial stiffness for some specimens tested by Al-Chaar et al. [8]. This might be due to the initial defects of the specimens as described by Al-Chaar et al. [8] while the analytical model assumes perfect geometry of the specimens and no initial damage.
- For the specimen tested by Salet et al. [9], the prediction of the analytical model can be improved if the prestressing tendons are modeled explicitly. However, since the cross-section of the beam is quite unique, a more sophisticated analytical model is needed to model the beam with prestressing tendons. In this case, future research is needed to properly model the 3D-printed PC beam in order to predict the response more accurately.

Acknowledgments

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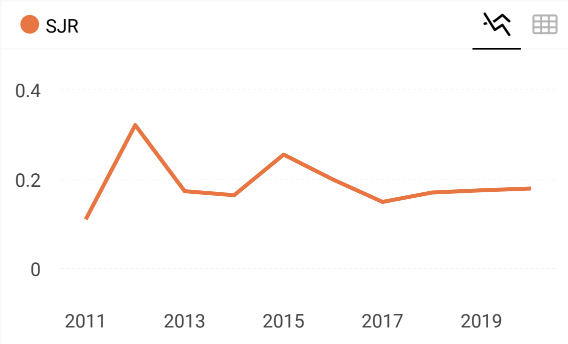

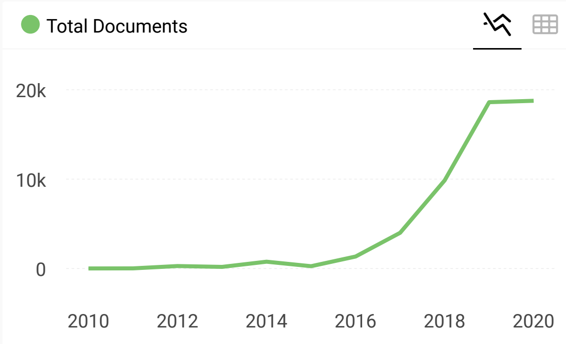

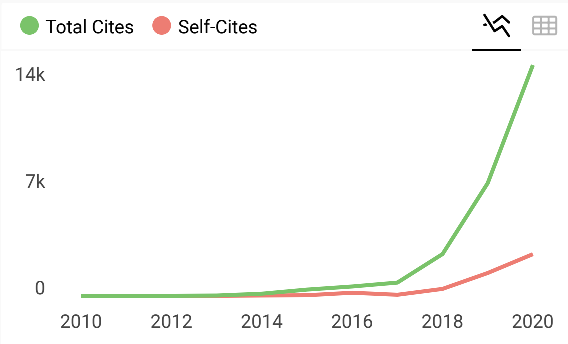

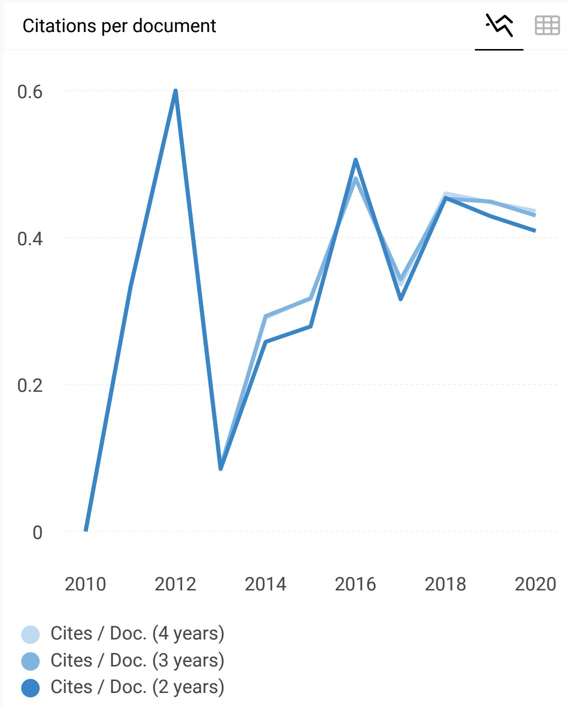

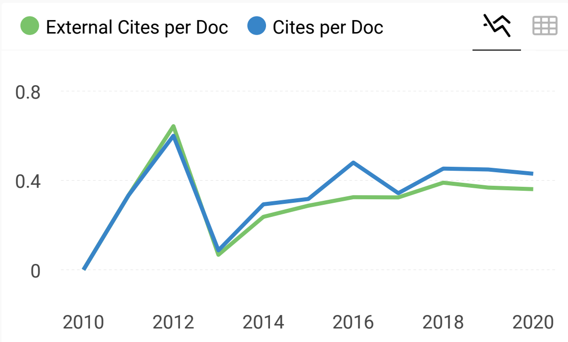

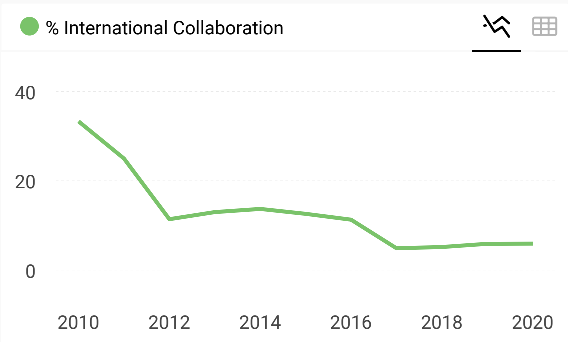

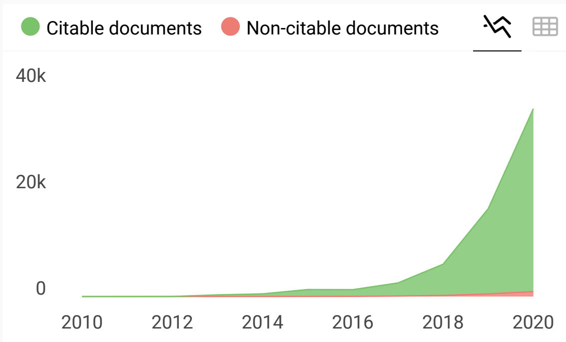

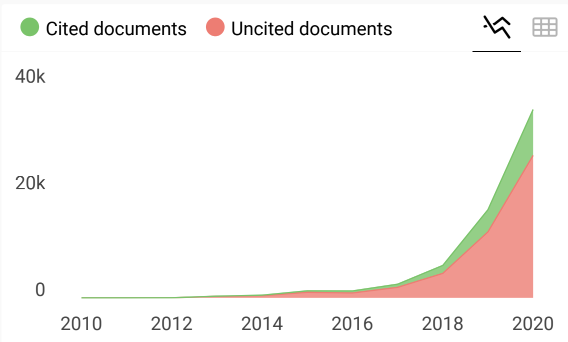

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