

Imperfections: using defects to program designer matter Meeussen, A.S.

Citation

Meeussen, A. S. (2021, May 26). *Imperfections: using defects to program designer matter*. *Casimir PhD Series*. Retrieved from https://hdl.handle.net/1887/3179459

Version:	Publisher's Version
License:	<u>Licence agreement concerning inclusion of doctoral thesis in the</u> <u>Institutional Repository of the University of Leiden</u>
Downloaded from:	<u>https://hdl.handle.net/1887/3179459</u>

Note: To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <u>https://hdl.handle.net/1887/3179459</u> holds various files of this Leiden University dissertation.

Author: Meeussen, A.S. Title: Imperfections: using defects to program designer matter Issue Date: 2021-05-26

Imperfections: using defects to program designer matter

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Leiden, op gezag van rector magnificus prof.dr.ir. H. Bijl, volgens besluit van het college voor promoties te verdedigen op woensdag 26 mei 2021 klokke 16:15 uur

door

Anne Sophia Meeussen geboren te Rotterdam, Nederland in 1990

Promotor	Prof.dr. M. L. van Hecke
Co-promotor	Dr. D. J. Kraft
Promotiecommissie	 Prof.dr. K. Bertoldi (Harvard University, Cambridge, USA) Prof.dr. C. Daraio (California Institute of Technology, Pasadena, USA) Prof.dr. A. Achúcarro Prof.dr. E. R. Eliel
Nederlandse titel	Imperfecties: het gebruik van defecten voor het programmeren van designer-materialen

Casimir PhD series, Delft-Leiden, 2021-03 ISBN 978-90-8593-469-1 An electronic version of this dissertation can be found at openaccess.leidenuniv.nl.

The work presented in this dissertation was conducted at AMOLF, Amsterdam, an institute of the Netherlands Organisation for Scientific Research (NWO), and at the Leiden Institute of Physics, Leiden University.

The cover shows a hand-sized groovy sheet, 3D-printed using a flexible material (courtesy of Jeroen Mesman-Vergeer), snapped into a spiralling shape.

Contents

1.	Intro	oductio	n	7
	1.1.		nportance of imperfections	7
	1.2.		ogical defects	8
	1.3.	Snap-t	hrough defects	10
2.	A spin-ice-inspired class of complex metamaterials			
	Abst	ract .		15
	2.1.	Introd	uction	15
	2.2.	Triang	ular building blocks	16
	2.3.	Compa	atible metamaterials	17
		2.3.1.	Parity of paths of internal bonds	19
		2.3.2.	Mapping compatible metamaterials to an antiferromagnetic Ising	
			model on the kagome lattice	21
		2.3.3.	Diversity of compatible metamaterial architectures	22
		2.3.4.	Compatible metamaterials with fully antiferromagnetic block spin	
			interactions	25
	2.4.		patible metamaterials	26
		2.4.1.	Triangle rotations as fundamental architectural transformations	27
		2.4.2.	A structural defect	27
		2.4.3.	A topological defect	28
	0 F	2.4.4.	More odd local loops	29
	2.5.		sions and outlook	30
	Аскі	nowledg	ements	30
3.			defects produce exotic mechanics in complex metamaterials	31
				31
			uction	31
	3.2.		g frustration: models and experiments	32
		3.2.1.	1	32
		3.2.2.		34
		3.2.3.	v 8 8	36
		3.2.4.	Comparing experiments and models	37
	3.3.		nical signature of defects	40
			Detection protocol: measuring the boundary	41
		3.3.2.	Probing the entire boundary	42
		3.3.3.	Hinge stiffness: the right value	44
		3.3.4.	Probing a few boundary blocks	44
		3.3.5.	Decay limits detection	47
	3.4.	3.3.6. Evotio	Error estimates	$48 \\ 49$
	J.4.	Exotic 3.4.1.	mechanics with topological defects	$\frac{49}{50}$
		3.4.1. 3.4.2.	Stress and deformation steering	$50 \\ 54$
		3.4.2. 3.4.3.	Mode splitting in the presence of topological defects	54 57
		0.1.0.	mode sphering in the presence of topological defects	01

Contents

			usions and outlook							
4.	•	Response evolution of mechanical metamaterials under architectural transfor- mations								
		nations								
	4.1.		luction							
	4.2.		mechanics: states of self stress and floppy modes							
	4.3.		urally complex mechanical metamaterials							
	4.4.		of self stress in superhexagons and larger metamaterials							
	4.5.		tectural defects							
	4.6.	-	nse evolution under architectural transformations							
		4.6.1.	0							
		4.6.2.	1 0 1							
			patible geometry							
		4.6.3.	Process II: supertriangle rotation from an incompatible to another							
			incompatible geometry							
		4.6.4.	Mechanical interpretation and consequences							
	4.7.		eering a stress response with architectural transformations							
	4.8.		usions and outlook							
	Ackı	nowledg	gements	. 85						
5.			le groovy sheets	87						
	Abst	tract .								
	5.1.	Introd	luction	. 88						
	5.2.	Makin	ng groovy sheets	. 95						
		5.2.1.	Geometry	. 95						
		5.2.2.	Fabrication	. 95						
	5.3.	Measu	ring groovy sheet shapes	. 104						
		5.3.1.	2D photography	. 104						
		5.3.2.	3D imaging	. 104						
	5.4.	In-pla:	ne elasticity of groovy sheets	. 110						
		5.4.1.	Groovy sheets are not symmetric	. 110						
		5.4.2.	Stiffness along the grooves	. 111						
		5.4.3.	Stiffness across the grooves	. 111						
		5.4.4.	Modelling stiffness	. 111						
		5.4.5.	A 3D sheet simulation	. 116						
	5.5.	Bistab	pility of grooves	. 119						
		5.5.1.	Making single defects	. 119						
		5.5.2.	Sheet size dependence	. 122						
	5.6.	Intera	ctions between defects	. 128						
		5.6.1.	Defects interact with their nearest neighbours	. 128						
		5.6.2.	Defects attract and repel	. 130						
		5.6.3.	Interactions via curvature							
	5.7.	Shapir	ng groovy sheets with scar lines	. 139						
		5.7.1.	A single scar							
		5.7.2.	Combining scars							
		5.7.3.	Parallel scars							
		5.7.4.	Understanding sheet shapes: outlook							

Contents

Ę	5.8. Conclusions and outlook	160
1	Acknowledgements	161
A. /	Appendices	163
1	A.1. Floppy motion of a triangular building block	163
	A.2. Constructing delocalized SS-states	165
1	A.3. Evolution of LB-spaces under architectural transformations	165
	A.3.1. Process I: compatible to incompatible metamaterial	168
	A.3.2. Process II: incompatible to incompatible metamaterial	169
	A.3.3. Process III: compatible to compatible metamaterial	170
	A.4. Mechanical interpretation of evolving LB-states	170
I	A.5. Derivation of stress response differences	173
	A.6. BoPET film properties	176
1	A.7. Spring-back, yielding, and groove design	179
1	A.8. Elasticity of groovy sheets: accordion model	183
I	A.9. 3D numerical sheet model	185
	A.9.1. Parameters	185
	A.9.2. Algorithm	185
	A.9.3. Energy and forces	186
1	A.10.Defect energetics in a 3D numerical sheet model	188
	A.11.Calculating surface curvature	189
1	A.12.Elastic model of groovy sheets with a single scar line	191
Bibl	liography	197
Sum	nmary	207
Sam	nenvatting	211
Pub	lications	215
Curi	riculum Vitae	217
Tha	nk you	219

You are trying to solve a problem. You're almost certainly halfway done, maybe more.

Jane Hirshfield