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The impact of skin tone on skin tolerance to shear in the context of pressure injuries: Theory and computer modeling

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Abstract

Objective: To investigate the impact of darker skin tones on skin tolerance to shear forces in the context of pressure injuries and to explore the mechanobiological hypothesis that people with darker skin may be at increased pressure injury risk due to altered biomechanical skin properties resulting from a lower water content as some literature suggests.

Methods: A computational finite element modeling framework was developed for this purpose, simulating skin with varying Poisson's ratios to represent different water content levels in the stratum corneum, focusing on the effects of ethnicity and water content on mechanical stresses in superficial skin during weightbearing postures. Mechanical properties of the tissues were based on literature values. Pure compression and compression with shear were applied to the skin model.

Results: The study found that a lower Poisson's ratio in the stratum corneum, indicating lower water content, is associated with higher tissue stresses and more intense stress concentrations, especially under combined compression and shear loading. The initial reduction in the Poisson's ratio had the most significant impact on increased tissue loading. These results supported the hypothesis that the lower water content in darker skin, resulting from increased trans-epidermal water loss, may lead to altered biomechanical behavior and increased pressure injury risk.

Conclusions: The modeling suggests that reduced water content and increased trans-epidermal water loss, notably present in darker skin tones, leads to higher stress concentrations within the stratum corneum, thus elevating the pressure injury risk. There is need for comprehensive clinical and biomechanical data across various skin tones to improve the practice of pressure injury prevention in individuals with darker skin.

Keywords: Pressure injury etiology; Superficial pressure ulcers; Ethnicity related risk; Stratum corneum and dermis fragility; Tissue biomechanics; Computational finite element simulations in wound care.

Abbreviations

3D	Three-dimensional
FE	Finite element
PI	Pressure injury
SC	Stratum corneum
TEWL	Trans-epidermal water loss
WC	Water content

1. Introduction

Pressure injuries (PIs) are localized damage to skin and/or underlying tissues resulting from sustained mechanical loading.[1] Superficial PIs are most often caused by excessive, sustained or repetitive shear forces acting on (fragile or vulnerable) skin.[1,2] If not mitigated, the combined factors of continuous tissue deformations, a resulting inflammatory response and a potential local ischemia in the affected region are likely to influence synergistically to exacerbate cell and tissue death and worsen the forming wound.[1,2] Several risk factors have been associated with an elevated risk of developing PIs, with immobility and impaired sensation being the main factors.[1] Importantly, the effects of sustained mechanical loading on cell and tissue viability are intricately linked to the anatomical structure and body morphology of the individual, their tissue composition, thickness and quality of the different soft tissue types at the relevant anatomical region, as well as the water content (WC) and tissue mechanical properties such as the stiffness of the affected soft tissues.[1-3]

Recent research strongly indicates that individuals with darker skin tones may exhibit greater vulnerability to PIs compared to individuals with lighter skin. Specifically, studies reveal that nursing home residents and acute care patients with darker skin are more prone to category 2 PIs and above.[4-10] The common (and perhaps simplistic) explanation for this observation is the apparent difficulty in diagnosing early-stage PIs in individuals with darker skin through the traditional visual skin assessments.[4-6,8-10] Socioeconomic factors, including lower healthcare quality standards, lack of proper insurance and impaired awareness, were also suggested to contribute to the PI prevalence difference between people with darker versus lighter skin tones.[5,11]

Studies comparing dark and white skin properties have revealed that the ranges and averages of skin layer thicknesses are statistically similar between the groups, however, the trans-epidermal water loss (TEWL) is typically higher for people with darker skin.[10,12-14] In other words, dark skin have a similar anatomy to that of light skin, but a different physiology, as dark skin tends to lose more water to the environment via evaporation,[10,12-14] which is very likely associated with lower basal WC levels in people with dark skin tones compared to those of light skin.[15-18] Specifically, skin moisture levels can be assessed using capacitance, conductance, impedance, and resistance sensors. It is well established that a greater WC in the skin leads to heightened capacitance and conductance due to alterations in the electrical properties of skin.[15] Conversely, dry skin tends to exhibit greater resistance and impedance in electrical conductivity. However, there remains a paucity of studies utilizing these methods to directly compare WC data between different ethnic groups. The seminal work in this area is by Johnson and Corah,[16] who examined basal skin resistance in both pediatric and adult populations. They measured resting levels of skin resistance over a 10-minute period, utilizing average values for comparing dark and white skin. Intriguingly, individuals with darker skin tones (in the two age categories) exhibited significantly higher galvanic resistance compared to the groups with light skin tones. Since the electrical resistance of skin is inversely correlated with its WC, it can be inferred that skin hydration levels were lower among the subjects with dark skin, a phenomenon partially attributed to ethnic differences in stratum corneum (SC) lipid levels.[12] Moreover, recent data on baseline lip hydration compiled by Gunt and Levy,[17] who conducted a comprehensive statistical analysis of sixteen clinical studies under standardized protocols, corroborates the notion of lower skin WC levels among individuals with dark skin tones compared to those with light skin. Although the Gunt and Levy[17] study did not focus on PIs, it highlights an important avenue for further research regarding ethnic susceptibility to PIs. The current study is therefore conducted under the premise of this assumption, namely, that people with darker skin tones typically have higher TEWL and lower WC levels than those of people with light skin tones. This assumption finds solid support in a substantial body of experimental evidence, first reported by Johnson and Corah,[16] and further analyzed by Wan et al.[12] and by Gunt and Levy,[17] as well as in a recent expert clinical opinion paper.[18]

Consequently, the typically lower WC in dark skin may lead to an altered, distinguished biomechanical behavior, potentially impairing the skin compressibility and elasticity, thus making it more vulnerable to PI formation. Specifically, a key tissue characteristic for understanding this behavior is the Poisson’s ratio, which is a fundamental mechanical property of all solid materials, including soft tissues. The Poisson’s ratio represents the relative deformation of a material in the direction perpendicular to the primary loading direction. A Poisson's ratio of exactly 0.5 represents a fully incompressible material with a high WC, for example saturated hydrogels.[19] To our knowledge, no specific research has been reported regarding evaluations of the direct relation between the Poisson's ratio of skin and its WC, however, it is well established that the SC contains remarkedly high amounts of water, approximately 30% to 50% of its dry weight.[20] Moreover, water is known to act as a plasticizer in skin (similarly to their effect on hydrophilic polymers), that is, if the hydration levels of the SC are low, e.g., at about 15% or below, the SC becomes brittle and fragile.[21,22] Based on this dermatological literature, it can be safely deduced that the Poisson’s ratio of skin and more specifically, of the SC, will decrease if the WC lowers, and that this will affect not only the tissue compressibility but also, will impact its stiffness, because the classic biomechanical engineering theory strongly couples the Poisson’s ratio with stiffness measures such as the elastic modulus. Clearly, skin stiffness alterations associated with its WC can indicate a change of the PI risk. Utilizing finite element (FE) modeling, this study therefore aims to investigate the impact of a lower Poisson’s ratio in the SC skin layer, which is considered to be associated with increased TEWL, on mechanical stress levels in the tissue during sustained compression and shear loading episodes in a clinical context of the PI risk in people with a dark skin tone.

Using computational modeling, the aim of this study was therefore to investigate the hypothesis suggesting that diminished WC in dark skin, stemming from the empirically observed, consistently heightened TEWL in this skin type, might result in altered biomechanical skin characteristics and an elevated risk of PIs for people with dark skin.

2. Methods

2.1. Underlying model assumptions

The Poisson's ratio of skin can vary depending on factors such as the specific anatomical location of skin tissue, its hydration level, and the age of the individual. However, typically for soft tissues like skin, Poisson's ratio ranges from approximately 0.3 to nearly 0.5.[23,24] This means that when a skin tissue is stretched in one direction, it tends to contract in the perpendicular direction with about third to half the strain. When the skin is more hydrated, it typically exhibits a higher Poisson's ratio, meaning the tissue biphasic material becomes more compliant and contracts more easily in the lateral direction when stretched. This is primarily because water molecules can act as plasticizers, increasing the ability of the hydrated skin to deform laterally. The current work tested the effects of decreasing the Poisson's ratio of the SC in the above range, i.e., from nearly 0.5 to 0.3, on the stress state of the SC when it is loaded in compression and shear, to simulate a lower WC for darker skin (as described in the Introduction). Importantly, anatomical studies to-date did not identify any consistent thickness, layer thickness or wrinkling / topography differences between dark and light skin tones,[14] and so, these were considered independent of ethnicity and identical between dark and white skins in the current modeling. The specification listing each geometrical dimension and topographical feature of the current model, and the rationales for their selections based on published experimental data (with cited references), are detailed in Tables 1 and 2 of Sopher and Gefen,[2] where the current skin model was initially described in the literature. This latter work provides essential context for our current study, serving as the modeling framework basis upon which our application to skin ethnicity research builds. In brief, the skin is composed of three layers of different mechanical properties: A naturally wrinkled 15-µm-thick SC; underneath, a less stiff 50-µm-thick viable epidermis (referred to as subepidermal nonechogenic band, SENEB, in dermatological imaging) which is also wrinkled; and an underlying elastic ~1-mm-thick elastic, deeper dermis (**Figure 1**).

2.2. Geometry

To examine the effects of the skin tone (i.e., ethnicity) and WC on the mechanical stresses in the superficial skin during weightbearing postures such as sitting or lying, a three-dimensional computational FE modeling framework was used, based on previous work of our research group.[2] A geometrical skin model, consisting of layered SC, SENEB and dermis was used **(Figure 1).** Two loading conditions were applied to the FE model, simulating pure compression and compression with shear. For the SC layer, seven different Poisson's ratio values, ranging between 0.495 to 0.3,[2] were used to simulate the water content in this layer; all the other layers of the skin model remained with the same properties through all the simulations.

The skin model simulated a three-dimensional (3D) wrinkled skin sample with a size of 3 X 3 X 1.3 mm (length × width × height). The topography of the skin wrinkles and the thickness for each layer, representing a young adult skin model, were adopted from the literature.[2,25] The 3D skin model was designed using SolidWorks 2015 (Dassault Systems, Vélizy-Villacoublay, France). Specifically, the wrinkles were created using a sinus function which resulted in a wrinkle width of 0.26 mm and amplitude of 0.12 mm peak-to-valley **(Figure 1)**. The skin was simulated to be compressed and sheared against a support surface with mechanical properties that are typical to hospital mattresses or wheelchair cushions (**Table 1**).[2,25-27] The support surface was modeled using the Abaqus FE software (Dassault Systems, Vélizy-Villacoublay, France).[28] Meshing of both the skin model and support surface was conducted by means of the ABAQUS FE software mesh generator. To analyze the stresses in the SC layer resulting from the bodyweight forces, a volume of interest (VOI) was defined in the form of a square area in the middle of the SC layer to avoid any edge-induced effects **(Figure 1).**

2.3. Mechanical properties of the model components

All the materials included in the current modeling, i.e., all the skin layers and the support surface were assumed to be homogenous and isotropic, and their constitutive laws and mechanical properties were adopted from the literature **(Table 1)**. Specifically, the support surface was modelled as a linear-elastic material with an elastic modulus of 70 kPa and a Poisson's ratio of 0.4**.**[2,29] The aforementioned support surface stiffness level is typical of a foam with density of ~30 kg/m^3 when subjected to large deformations, and represents a soft foam mattress topper which is characteristic to medical mattresses.[29,30] The dermis and SENEB were assumed to behave as nearly incompressible, hyperelastic Neo-Hookean materials[2,25] with a strain energy density function W:

$$W = C_{10}(\overline{I_1} - 3) + \frac{1}{D_1}(J_{el} - 1)^2 \quad (1)$$

where $\overline{I_1}$ is the first invariant of the right Cauchy-Green deformation tensor, J_{el} is the determinant of the deformation gradient tensor and C_{10} and D_1 are material parameters representing the shear (μ_0) and the bulk (K_1) modulus, respectively and defined as: $C_{10} = \frac{\mu_0}{2}, D_1 = \frac{2}{K_1}$.

The SC was assumed to behave as a hyperelastic Neo-Hookean material. As mentioned above, the Poisson's ratio of the SC was defined differently for each model configuration (variant), to represent different water content levels in this layer. The shear and bulk moduli of the SC were derived from the elastic modulus and Poisson's ratio values using the standard transformation equations:

$$\mu_0 = \frac{E}{2(1+\nu)} \tag{2}$$

$$K_1 = \frac{E}{3(1-2\nu)} \tag{3}$$

where E is the elastic modulus of the SC layer adopted from the literature[2,25] and ν is the specific Poisson's ratio value for each configuration **(Table 2).**

2.4. Boundary conditions and interfaces

In general, studies found that contact pressures between the body and medical mattresses typically range between 2 and 12 kPa for normal lying posture conditions, and are most predominately affected by the anatomical site, e.g., differ between approximately 2 kPa under the sacral/buttock area and up to 12 kPa under the heels.[31-35] For the purpose of the current modeling, we selected the midrange value of 7 kPa. This interface pressure was represented through downward displacement applied to the skin model top surface until a force of approximately 0.063 N, perpendicular to the surface, was reached. The achieved force represented the above average interface pressure applied to a $9\ \mathrm{mm}^2$ area. The top skin surface was fixed in all the other directions. To further evaluate the effect of shear and compression combined, a horizontal displacement of 0.25 mm, perpendicular to the direction of the wrinkles, was imposed. Frictional sliding contact was defined between the skin and the support surface, with a coefficient of friction (COF) of 0.42 which represents dry contact of skin with commercially available hospital fabrics. [26,27,32,36] The different skin layers were assigned tied interfaces (i.e., a “no-slip” condition) at the tissue-tissue boundaries. The inferior area of the support surface was fixed for translations in all directions and for all rotations.

2.5. Numerical method

The skin and support surface were meshed using four-node tetrahedral elements. Skin layers were meshed using first order linear hybrid elements (type C3D4H) with higher element density at the thinner layers. The support surface was mashed using first order linear elements (type C3D4). The numbers of elements used to mesh each of the model components are detailed in **Table 1**. The FE simulations were set up and solved using the Abaqus/CAE 2020 software suit. The runtime for each model variant was approximately 1 hour using 6 parallel cores of a 64-bit Windows 10 PC with Intel Core i7 processor, 3.00 GHz clock speed and 32 GB of RAM.

2.6. Outcome measures and model validation

For each model variant, characterized by a different Poisson’s ratio value of the SC layer (**Table 2**), the tissue stress distribution was calculated within the SC VOI, as shown in **Figure 2** (for the two extremes of the SC Poisson’s ratios in the case of **Figure 2**). A histogram of the VOI stress distribution was then plotted for the fourth quartile of the SC stress values to focus on the stress concentrations in the SC (**Figure 3**). The effect of the water content in the SC (which is represented by the Poisson’s ratio of this layer) on the stress concentration exposure in the SC was then further evaluated, by calculating the change in the area bounded between the corresponding SC stress histogram curve and the *x*-axis, with respect to the curve of the nearly-incompressible, i.e., fully-hydrated SC configuration ($\nu = 0.495$).

3. Results

For both loading cases of compression and compression with shear, the effective stress distribution within the SC was substantially influenced by the Poisson's ratio, as evident visually (**Figure 2**) and quantitatively (**Figure 3**). Specifically, a lower Poisson's ratio of the SC, indicating a lower SC water content, is associated with elevated tissue stresses and more intense stress concentrations at the peaks of the wrinkles, particularly when subjected to combined compression and shear loads. Consistently, the stress exposure histograms for the SC demonstrated that the lower its Poisson's ratio, the higher is the SC exposure to stresses and the greater are the maximal SC stress values (**Figure 3**). For example, reducing the Poisson's ratio from 0.495 to 0.47 resulted in 50% and 70% greater SC exposures for the combined compression and shear and the compression-only conditions, respectively (**Figure 3**, right panels). The effect of the Poisson's ratio on the SC stress state was more pronounced for the initial reduction in ν values and then moderated, indicating that it is the initial water loss that has the most influence on the increased SC loading. Importantly, for both loading conditions, the SC exposure to stresses approximately doubled from the fully hydrated (ν =0.495) to the most severe water loss condition ($\nu = 0.3$) that was simulated (**Figure 3**, right panels).

4. Discussion

Published research indicates that individuals with darker skin tones face a greater risk of developing PIs.[4-14] The common explanation for this disparity attributes it to inadequate clinical skin assessments in individuals with darker skin, resulting in the poorer (early) diagnosis and prevention of PIs.[4-14] In this study, we explored a novel hypothesis that goes beyond this somewhat simplistic explanation. Our new mechanobiological hypothesis suggests that, apart from the previously mentioned factors, people with darker skin tones may also be at an increased risk of PI formation due to ethnicity-related factors influencing their biomechanical skin properties.[10] Specifically, affected by an increased TEWL of dark skin compared to white skin, the steady-state water content in the SC layer of people with darker skin tones is very likely typically lower,[10,12-14,16-18,37] resulting in alterations in the mechanical properties of this layer. Accordingly, we tested the relation between the Poisson's ratio of the tissue simulating different WC levels in the SC and the mechanical stresses acting on the tissue, under compression and for compression combined with shear. Our results indicated that the effective stresses in the SC were significantly higher for lower Poisson's ratios, for both loading conditions. Furthermore, it is the initial reduction in the Poisson's ratio that leads to a drastic increase in the stress levels at the SC layer (**Figure 3).** Previous studies showed that drier skin and dry SC in particular, are more prone to microdamage compared to healthy skin and accordingly, dry skin is a risk factor for PI formation.[1,18,37-40] Studies also showed that people with darker skin tones have drier skin compared to those with white skin.[13,14] Consequently, our current results support the notion of a self-perpetuating cycle of shear damage within the SC, progressively lowering the WC and elevating the TEWL and ultimately, increasing the PI risk as illustrated in **Figure 4**. It is crucial to acknowledge that, for the sake of practicality in the simulation computations, our study primarily focused on changes in the Poisson's ratio of the SC layer resulting from an increased TEWL. However, it is plausible that elevated TEWL and decreased WC levels could affect additional biophysical and biomechanical skin properties, such as the pH, viscoelasticity parameters and others.[12,14,37,38,40] These factors could further intensify the vicious cycle leading to PI in people with darker skin tones. Despite the increased susceptibility of individuals with darker skin tones to PIs, the existing clinical knowledge predominantly stems from studies conducted on individuals with white skin.[4-8,10] Unfortunately, there is evident paucity of published data regarding biomechanical differences between skin tissues of various tones, encompassing diverse ethnic backgrounds.[10,13] This knowledge gap profoundly impacts the effectiveness of strategies for PI prevention, diagnosis, and treatment in patients with darker skin.

Interestingly, the simulations in **Figure 2** demonstrate that when skin with wrinkles is compressed and sheared against a support surface, skin mechanical stresses maximize at the peaks of the wrinkles. This phenomenon occurs due to the localized concentrations of forces at the small region of contact between the crests of the wrinkles and the support surface. Specifically, wrinkles on the skin create irregularities in the skin surface topography, leading to variations in the contact pressure distribution (at the millimeter-scale of the model). When shear forces are applied, these irregularities further distort and amplify the stress concentrations at the peaks of the wrinkles. Indeed, in **Figure 3a**, for compression and shear combined, it is shown that the histograms of the stress distribution over the 4th-quartile of the stress domain in the SC shifted to the right, i.e., to the greater stress values, compared to the compression-only loading case (**Figure 3b**). In other words, the application of shear contributed to a less uniform stress pattern in the SC, intensifying the peaks of the stress concentrations in this layer (**Figures 2** and **3**). In real skin tissues, which vary across individuals, the orientation and morphology (depth and width) of the wrinkles can influence the distribution of the mechanical stresses at the skin surface under bodyweight or medical device loads. For example, wrinkles aligned perpendicular to the direction of shear may experience different stresses than wrinkles oriented parallel to the shear direction. Understanding the mechanics of wrinkled skin under shear (which is relevant for example, to geriatric patients) may provide insights to the design of support surfaces or cushioning materials that address the needs of patients with fragile, wrinkled skin.

This first-of-its-kind computational modeling framework has some limitations that should be considered when interpreting the current results. First, no literature directly addresses the effects of WC on the Poisson's ratio of the SC and accordingly, this work should be perceived as theoretical and as a proposed mechanism of damage in darker skin in the context of PI risk, which still requires experimental verification. Nonetheless, it is intuitive for trained biomechanical engineers that a reduced WC would compromise the incompressibility of the tissue, thereby exposing it to greater localized sustained micro-deformations and thereby, greater likelihood of skin damage formation. In this context, our results show that the effect of increased loading of the SC is more pronounced upon the initial reduction in Poisson's ratio. Furthermore, the skin layers and wrinkle dimensions were based on a detailed and validated biomechanical model formulated by Magnenat-Thalmann and colleagues.[25] However, this model simplifies the wrinkle geometry, assuming uniformity in the wrinkling pattern as opposed to representing the complex nonuniform microarchitecture of real tissue wrinkles. The skin is also assumed to be isotropic, i.e., neglecting its anisotropic nature. In addition, the hypodermis has not been incorporated into the model. Another noteworthy point is that COFs may vary based on individual skin characteristics, bedlinen types, and moisture levels at the body-support interfaces. Lastly, our 3D skin model, which is based on our previously published research,[2] is relatively small, with a limited volume of interest to avoid edge and boundary effects. Consequently, any data interpretation based on the current modeling work should focus on trends in tissue loading states corresponding to the SC Poisson's ratios, representing the WC levels in the SC, rather than on the specific SC stress values. Future extension of our modeling may include more complex wrinkle shapes and anisotropic skin properties, as well as testing against different support surface types.

In conclusion, this study was performed under the new premise that lower WC in darker skin, together with elevated TEWL in this skin type, might alter the biomechanical behavior of skin (and the SC behavior in particular), in a manner that increases the PI risk of people with darker skin. In the wrinkled skin topography (considering that some level of wrinkling always exists in the adult human skin), mechanical stresses in the skin maximize at the peaks of wrinkles when compressed and sheared against a support surface. This phenomenon arises due to concentrated forces at the contact points between wrinkle crests and the external surface, which contribute to the inhomogeneity in the contact pressure distribution (at the micro-scale), and specifically, to the formation of stress concentrations in the SC. Shear forces further amplify these stress concentrations at the wrinkle peaks. Understanding these biomechanical phenomena in wrinkled skin, particularly relevant for geriatric patients, could inform the design of support surfaces or cushioning materials for individuals with fragile and aged skin. Another important perspective stemming from understanding these interactions is in the context of ethnicity, where the WC and TEWL that appear to depend on the ethnical origin, influence the above phenomena. Our study employed FE modeling to evaluate the impact of lower WC and increased TEWL, notably present in darker skin tones, on the stress state within the SC layer. Our current findings compellingly suggest that reduced WC and elevated TEWL levels can lead to a rise in the stress concentrations within the SC, thus increasing the PI risk, which provides a valuable insight into the increased vulnerability of darker skin types to PIs. Finally, the work reported herein underscores the need for acquisition of comprehensive physiological, clinical and biomechanical data and knowledge for various adult and pediatric skin tones, in order to achieve better wound prevention and care for people with all skin types.

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Figure captions

Figure 1	Geometry of the computational (finite element) skin model: (a) The skin model consists of 3-layer with the surface wrinkles facing the support surface, which is fixed for all movements at the bottom. As a first step in loading the model, a downward displacement is applied until reaching a mean contact pressure of 7 kPa, which is typical for a weightbearing contact of the pelvic region with a support surface. A second loading step of a horizontal (shear) displacement of 0.25 mm is then applied while the skin is compressed against the support surface. (b) A magnification of the wrinkles showing the model components of the stratum corneum (SC), subepidermal non-echogenic band (SENEB) and deep dermis. (c) View of the entire model domain. (d) The volume of interest (VOI) of the SC model component for calculations of tissue exposure to stresses.
Figure 2	The effective stratum corneum (SC) stresses for the (left panel) highest ($\nu = 0.495$) and (right panel) lowest ($\nu = 0.3$) Poisson's ratios of the SC, under loading condition of (a) combined compression and shear and (b) compression only. The elastic modulus of the SC was set as 6.0 MPa for all the shown configurations.
Figure 3	The volumetric exposures of the stratum corneum (SC) in the volume of interest (VOI) to effective stresses in the 4th-quartile (left panels) and the area under the curve values for each configuration in respect to a SC Poisson's ratio of 0.495 (right panels), for (a) combined compression and shear and (b) compression only. The histograms show the volumetric stress exposures in the thin (only 15-µm-thick) SC, i.e., there is a negligible stress gradient (or stress variation) along the depth of the SC. Of note, the *x*-axis ranges are the 4th-quartiles of the SC stress values (per each loading configuration), to focus on the stress concentrations in the SC and in order to provide insight into the highest stress values in the SC stress distribution (shown in **Figure 2**). This is made in the context of the physiological water barrier function of the SC, in limiting trans-epidermal water loss (TEWL), considering that excessive SC exposure to high stresses that compromise its structural integrity, can eventually damage the barrier and hence increase the TEWL.
Figure 4	Conceptual description of the vicious cycle of shear damage in dark stratum corneum (SC) which progressively increases the trans-epidermal water loss (TEWL).

Tables

Table 1: Mechanical, geometrical, and numerical characteristic of the model components. * denotes 'Per configuration' and specific values are detailed in Table 2. SC= stratum corneum; SENEB= subepidermal non-echogenic band.

Material	Thickness [mm]	Elastic modulus [MPa]	Poisson's ratio	Shear modulus [MPa]	Bulk modulus [MPa]	Number of mesh elements
SC	0.015	6.0	*	*	*	62,430
SENEB	0.05	0.05	0.495	0.02	1.7	92,274
Deep dermis	1.235	0.6	0.495	0.2	19.9	295,744
Support surface*	10	0.07	0.4	-	-	66,180

***The support surface material in the model is 10-mm-thick (**Table 1**) whereas the modeled skin tissue thickness is ~1.3 mm, i.e., the thickness of the support surface material is approximately 7.7-times that of the modeled skin, to avoid potential Saint-Venant edge effects (this does not cause any excessive compression of the support surface material given the above proportion).

Table 2: The mechanical properties of the stratum corneum for each model configuration.

Configuration	Elastic modulus [MPa]	Poisson's ratio	Shear modulus [MPa]	Bulk modulus [MPa]
A	6.0	0.495	2	200
B	6.0	0.47	2.03	33.2
C	6.0	0.45	2.06	19.9
D	6.0	0.41	2.12	11.1
E	6.0	0.385	2.16	8.67
F	6.0	0.35	2.2	6.65
G	6.0	0.3	2.3	4.99

Katz T, Gefen A. Impact of Skin Tone on Skin Tolerance to Shear in the Context of Pressure Injuries: Theory and Computer Modeling. Adv Skin Wound Care. 2025 Mar 1;38(2):105-111. doi: 10.1097/ASW.0000000000000270.

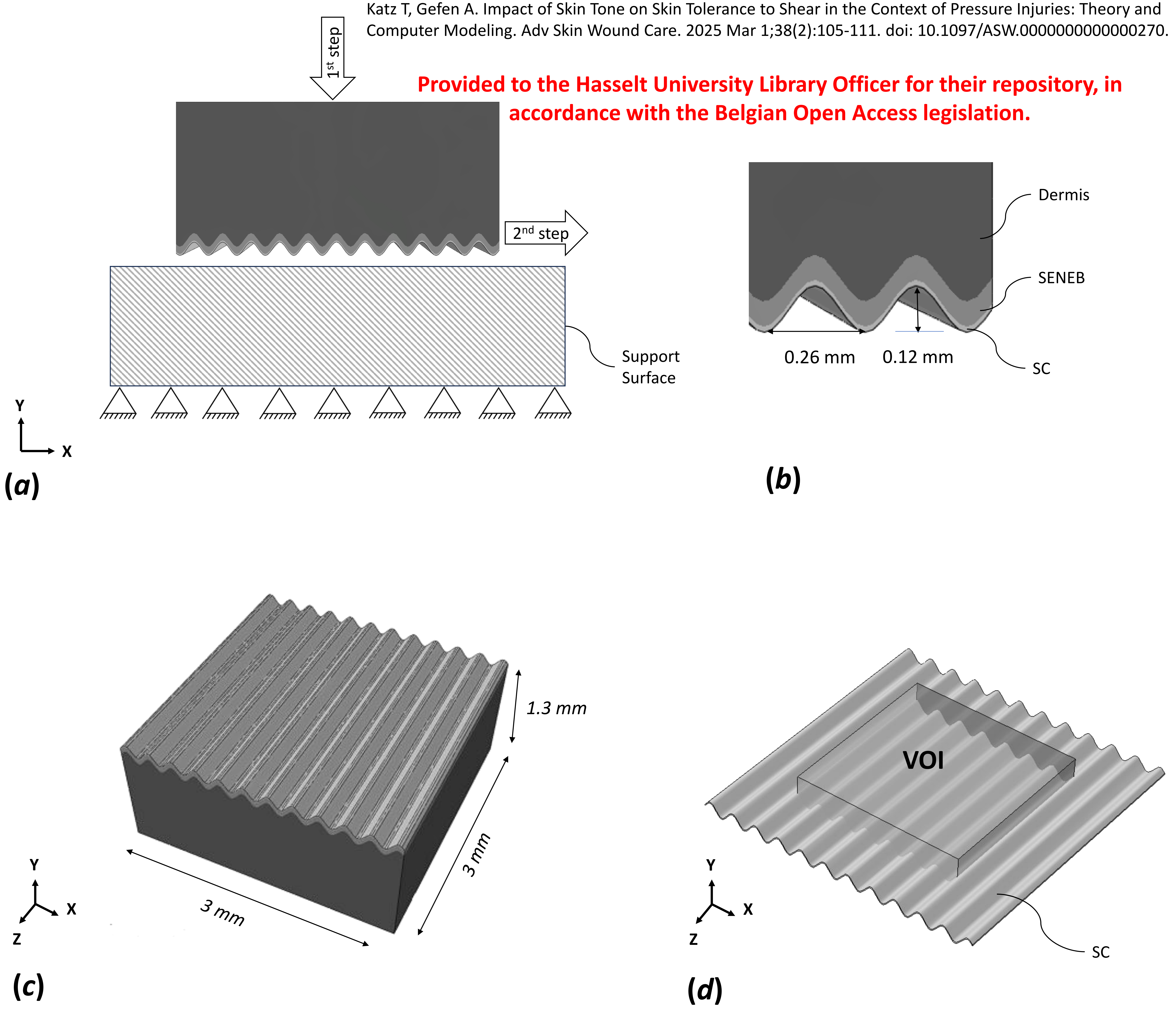

Figure 1

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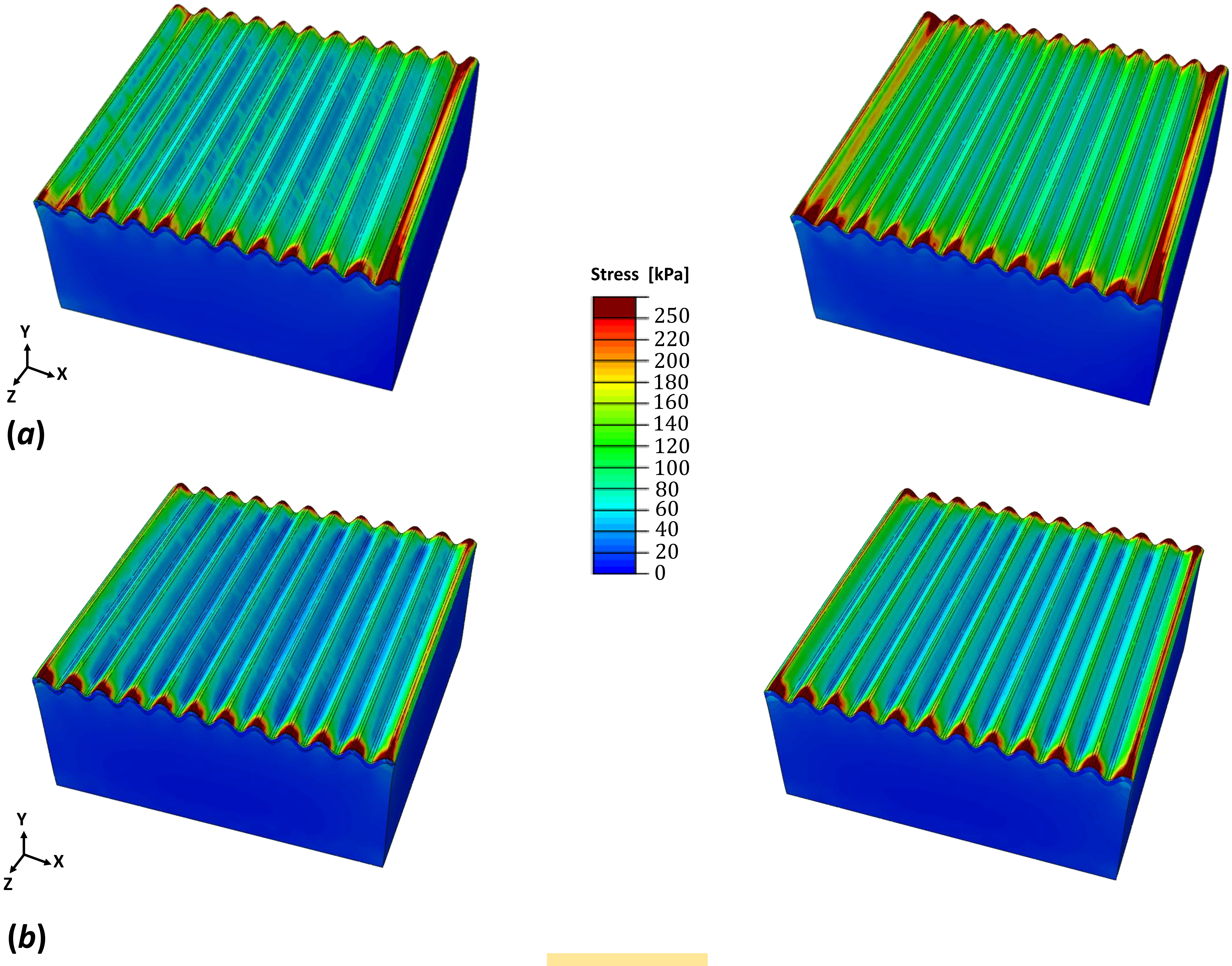

Figure 2

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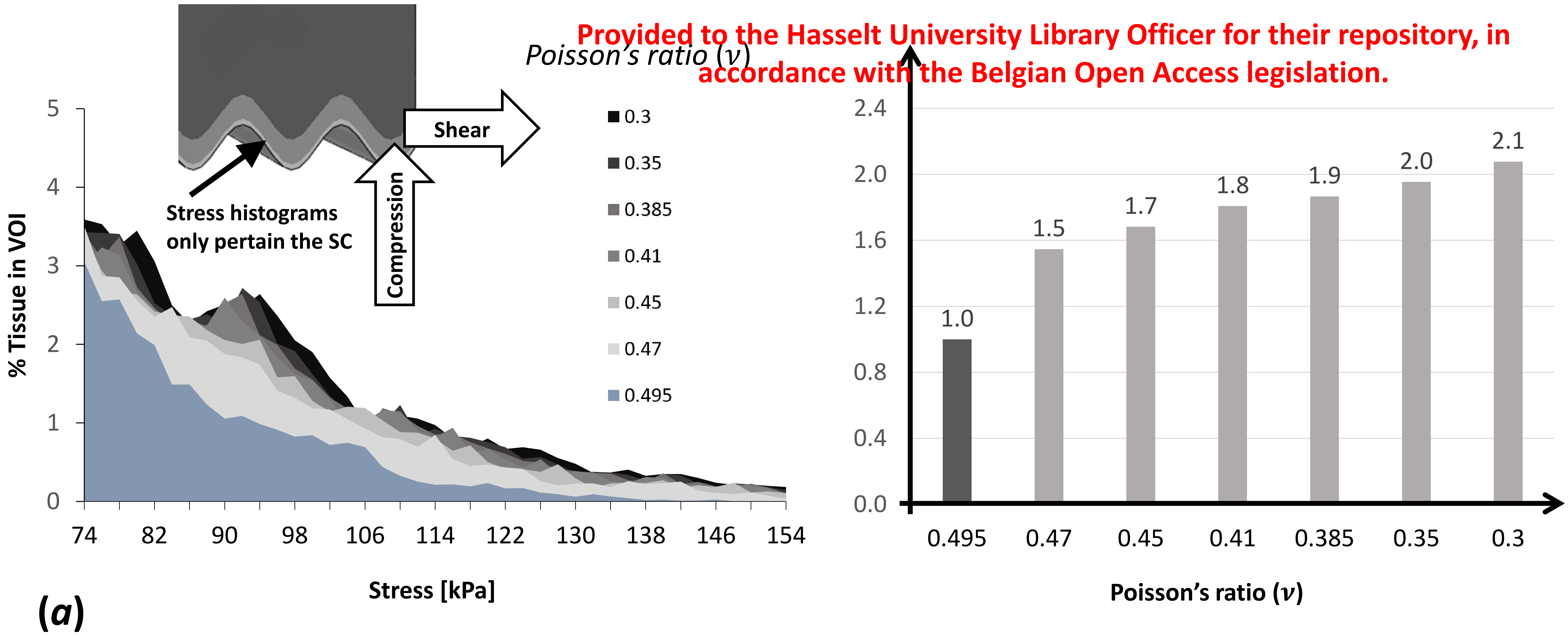

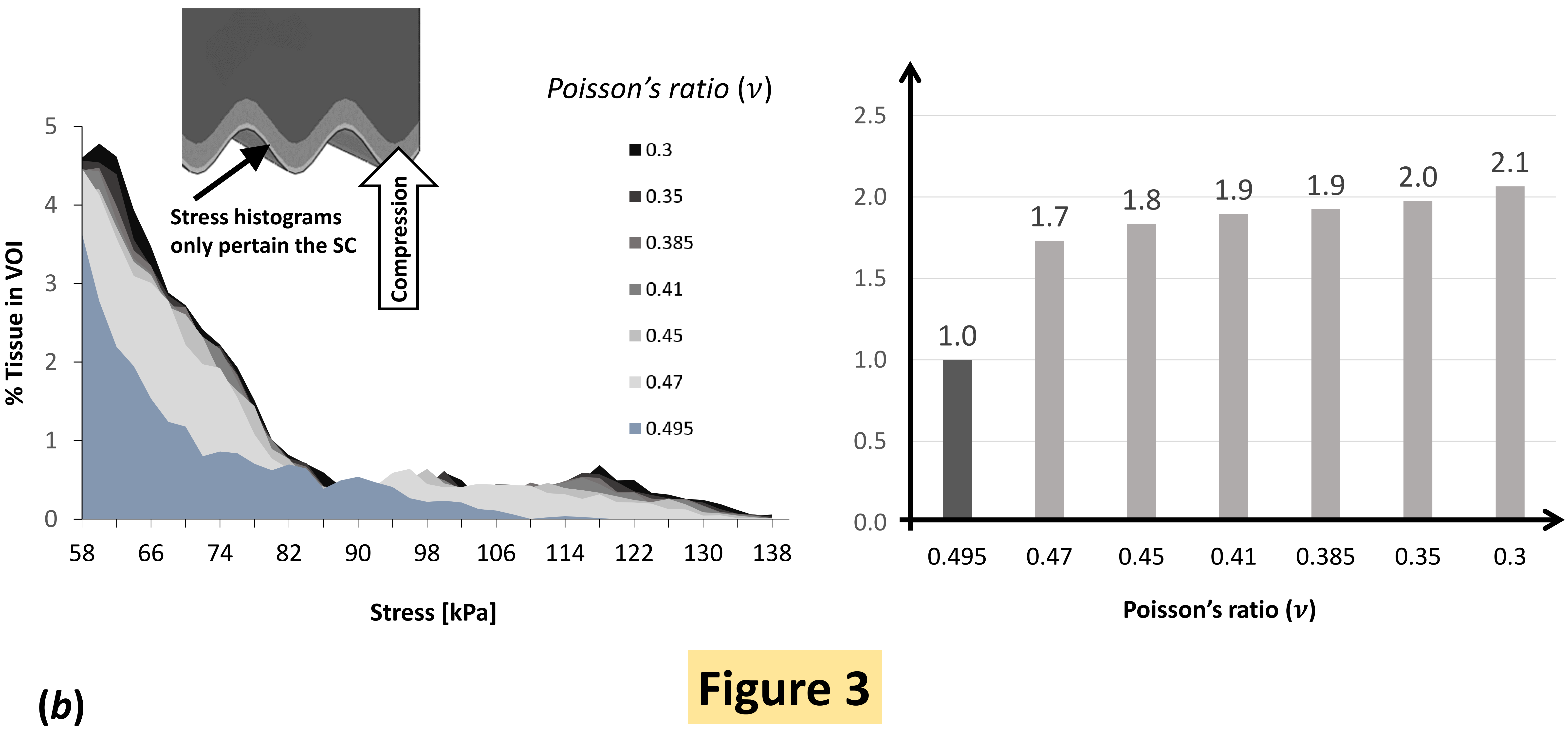

Figure 3

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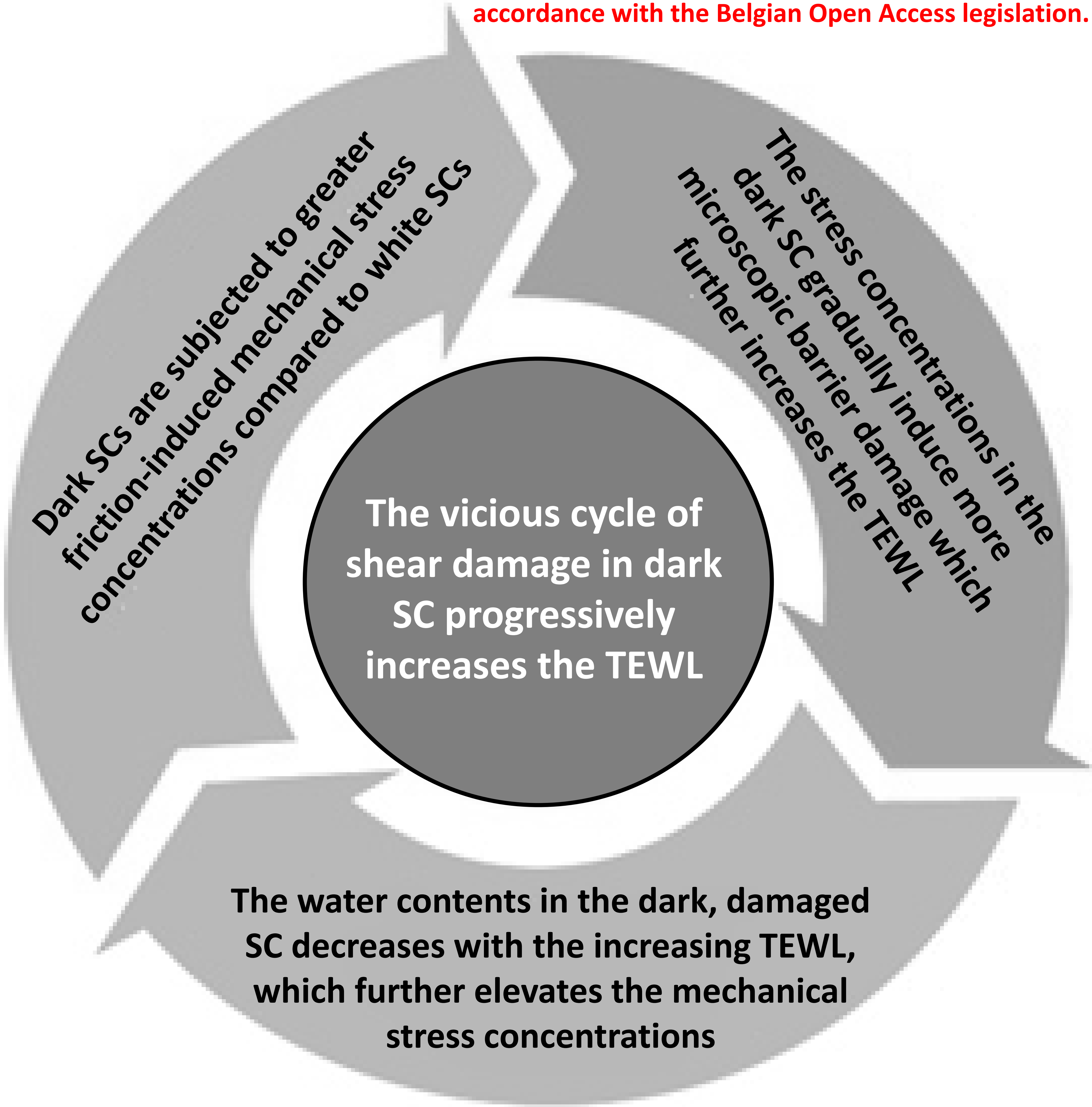

Figure 4