



OXFORD CENTRE FOR COLLABORATIVE APPLIED MATHEMATICS

Report Number 12/17

**Weyl Geometry and the Nonlinear Mechanics of Distributed Point
Defects**

by

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The date of receipt and acceptance will be inserted by the editor

Abstract: In this paper we obtain the residual stress field of a nonlinear elastic solid with a spherically-symmetric distribution of point defects. The material manifold of a solid with distributed point defects – where the body is stress-free – is a flat Weyl manifold, i.e. a manifold with an affine connection that has non-metricity but both its torsion and curvature tensors vanish. Given a spherically-symmetric point defect distribution, we construct its Weyl material manifold using Cartan’s moving frames. Having the material manifold the anelasticity problem is transformed to a nonlinear elasticity problem; all one needs to calculate residual stresses is to find an embedding into the Euclidean ambient space. In the case of incompressible neo-Hookean solids we calculate the residual stress field. We finally consider the example of a finite ball of radius R_o and a point defect distribution uniform in a ball of radius R_i and vanishing elsewhere. We show that the residual stress field inside the ball of radius R_i is uniform and hydrostatic. We also prove a nonlinear analogue of Eshelby’s celebrated inclusion problem for a spherical inclusion in an isotropic incompressible nonlinear solid.

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1. Introduction

The stress field of a single point defect in an infinite linear elastic solid was obtained by Love [26] almost ninety years ago. He observed a $1/r^3$ singularity. For distributed defects, Eshelby [12] showed that for a body with a uniform distribution of point defects, in the framework of linearized elasticity, the body expands uniformly. In other words, a uniform distribution of point defects is stress-free (if the body is not constrained on its boundaries)¹. Such calculations for nonlinear solids have not been done to this date. In the linear elasticity setting, point defects are modeled as centers of expansion or contraction [16]. In the nonlinear framework presented in this paper, we start with a distributed point defect and use non-metricity in the material manifold to model the effect of point defects.

It has been known for a long time that the mechanics of solids with distributed defects can be formulated using non-Riemannian geometries [23, 24, 4, 5]. In [41] we presented a comprehensive theory of the mechanics of distributed dislocations based on Riemann-Cartan geometry. We showed that in the geometric framework several examples of residual stress field of solids with distributed dislocations can be solved analytically. We calculated the residual stress field of several examples analytically. Later in [42], we extended the geometric theory to the mechanics of solids with distributed disclinations. In the case of both dislocations and disclinations there are exact solutions in the framework of nonlinear elasticity [33, 44, 2].

While it has been noted that the geometric object relevant to point defects is non-metricity [14, 10, 18, 25, 28], there are no exact nonlinear solutions for point defects in the literature. In other words, the coupling between the geometry and the mechanics of point defects is missing. The purpose of this paper is to develop a fully geometric and exact (in the sense of elasticity) theory of distributed point defects. As an application of this geometric theory, we obtain the stress field of a spherically-symmetric distribution of point defects in a neo-Hookean solid. We also prove a nonlinear analogue of Eshelby's celebrated inclusion problem for a spherical inclusion in an isotropic incompressible nonlinear solid.

This paper is structured as follows. In §2 we briefly review some basic definitions and concepts from differential geometry and, in particular, Cartan's moving frames and Weyl geometry. Kinematics and equations of motion for nonlinear elasticity and anelasticity are discussed in §3. In §4 we look at the problem of a spherically-symmetric distribution of point defects. Using Cartan's structural equations we obtain an orthonormal coframe field and hence the material metric. We then make a connection between the material metric and the volume

¹ We show in this paper that for an incompressible nonlinear solid this result still holds.

density of point defects using a compatible volume element in the Weyl material manifold. Having the material metric we then calculate the residual stress field. Next, we study an example of point defect distribution uniform in a small ball and vanishing outside the ball. We show that for any isotropic incompressible nonlinear solid the residual stress field inside the small ball is uniform. This is the nonlinear analogue of Eshelby's celebrated inclusion problem. We then show that a uniform point defect distribution is the only spherically-symmetric zero-stress point defect distribution. Finally, we compare the linear and nonlinear solutions for radial stress distribution.

2. Non-Riemannian Geometries and Cartan's Moving Frames

2.1. Riemann-Cartan manifolds. We tersely review some elementary facts about affine connections on manifolds and geometry of Riemann-Cartan and Weyl manifolds. For more details see [36, 6, 30, 31, 17, 20, 34]. A linear (affine) connection on a manifold \mathcal{B} is an operation $\nabla : \mathcal{X}(\mathcal{B}) \times \mathcal{X}(\mathcal{B}) \rightarrow \mathcal{X}(\mathcal{B})$, where $\mathcal{X}(\mathcal{B})$ is the set of vector fields on \mathcal{B} , such that $\forall f, f_1, f_2 \in C^\infty(\mathcal{B}), \forall a_1, a_2 \in \mathbb{R}$:

$$i) \quad \nabla_{f_1 \mathbf{X}_1 + f_2 \mathbf{X}_2} \mathbf{Y} = f_1 \nabla_{\mathbf{X}_1} \mathbf{Y} + f_2 \nabla_{\mathbf{X}_2} \mathbf{Y}, \quad (1)$$

$$ii) \quad \nabla_{\mathbf{X}}(a_1 \mathbf{Y}_1 + a_2 \mathbf{Y}_2) = a_1 \nabla_{\mathbf{X}}(\mathbf{Y}_1) + a_2 \nabla_{\mathbf{X}}(\mathbf{Y}_2), \quad (2)$$

$$iii) \quad \nabla_{\mathbf{X}}(f \mathbf{Y}) = f \nabla_{\mathbf{X}} \mathbf{Y} + (\mathbf{X}f) \mathbf{Y}. \quad (3)$$

$\nabla_{\mathbf{X}} \mathbf{Y}$ is called the covariant derivative of \mathbf{Y} along \mathbf{X} . In a local chart $\{X^A\}$, $\nabla_{\partial_A} \partial_B = \Gamma^C_{AB} \partial_C$, where Γ^C_{AB} are Christoffel symbols of the connection and $\partial_A = \frac{\partial}{\partial x^A}$ are natural bases for the tangent space corresponding to a coordinate chart $\{x^A\}$. A linear connection is said to be compatible with a metric \mathbf{G} of the manifold if

$$\nabla_{\mathbf{X}} \langle \mathbf{Y}, \mathbf{Z} \rangle_{\mathbf{G}} = \langle \nabla_{\mathbf{X}} \mathbf{Y}, \mathbf{Z} \rangle_{\mathbf{G}} + \langle \mathbf{Y}, \nabla_{\mathbf{X}} \mathbf{Z} \rangle_{\mathbf{G}}, \quad (4)$$

where $\langle \cdot, \cdot \rangle_{\mathbf{G}}$ is the inner product induced by the metric \mathbf{G} . It can be shown that ∇ is compatible with \mathbf{G} if and only if $\nabla \mathbf{G} = \mathbf{0}$, or in components

$$G_{AB|C} = \frac{\partial G_{AB}}{\partial X^C} - \Gamma^S_{CA} G_{SB} - \Gamma^S_{CB} G_{AS} = 0. \quad (5)$$

An n -dimensional manifold \mathcal{B} with a metric \mathbf{G} and a \mathbf{G} -compatible connection ∇ is called a Riemann-Cartan manifold [7, 8, 9, 19].

The torsion of a connection is defined as

$$\mathbf{T}(\mathbf{X}, \mathbf{Y}) = \nabla_{\mathbf{X}} \mathbf{Y} - \nabla_{\mathbf{Y}} \mathbf{X} - [\mathbf{X}, \mathbf{Y}]. \quad (6)$$

In components in a local chart $\{X^A\}$, $T^A_{BC} = \Gamma^A_{BC} - \Gamma^A_{CB}$. ∇ is symmetric if it is torsion-free, i.e. $\nabla_{\mathbf{X}} \mathbf{Y} - \nabla_{\mathbf{Y}} \mathbf{X} = [\mathbf{X}, \mathbf{Y}]$. On any Riemannian manifold $(\mathcal{B}, \mathbf{G})$ there is a unique linear connection ∇ that is compatible with \mathbf{G} and is torsion-free. This is the Levi-Civita connection. In a manifold with a connection the curvature is a map $\mathcal{R} : \mathcal{X}(\mathcal{B}) \times \mathcal{X}(\mathcal{B}) \times \mathcal{X}(\mathcal{B}) \rightarrow \mathcal{X}(\mathcal{B})$ defined by

$$\mathcal{R}(\mathbf{X}, \mathbf{Y}) \mathbf{Z} = \nabla_{\mathbf{X}} \nabla_{\mathbf{Y}} \mathbf{Z} - \nabla_{\mathbf{Y}} \nabla_{\mathbf{X}} \mathbf{Z} - \nabla_{[\mathbf{X}, \mathbf{Y}]} \mathbf{Z}, \quad (7)$$

or in components

$$\mathcal{R}^A_{BCD} = \frac{\partial \Gamma^A_{CD}}{\partial X^B} - \frac{\partial \Gamma^A_{BD}}{\partial X^C} + \Gamma^A_{BM} \Gamma^M_{CD} - \Gamma^A_{CM} \Gamma^M_{BD}. \quad (8)$$

2.2. Cartan's moving frames. Consider a frame field $\{\mathbf{e}_\alpha\}_{\alpha=1}^N$ that at every point of a manifold \mathcal{B} forms a basis for the tangent space. Assume that this frame is orthonormal, i.e. $\langle\langle \mathbf{e}_\alpha, \mathbf{e}_\beta \rangle\rangle_{\mathbf{G}} = \delta_{\alpha\beta}$. This is, in general, a non-coordinate basis for the tangent space. Given a coordinate basis $\{\partial_A\}$ an arbitrary frame field $\{\mathbf{e}_\alpha\}$ is obtained by a $GL(N, \mathbb{R})$ -rotation of $\{\partial_A\}$ as $\mathbf{e}_\alpha = F_\alpha^A \partial_A$ such that orientation is preserved, i.e. $\det F_\alpha^A > 0$. For the coordinate frame $[\partial_A, \partial_B] = 0$ but for the non-coordinate frame field we have

$$[\mathbf{e}_\alpha, \mathbf{e}_\alpha] = -c^\gamma_{\alpha\beta} \mathbf{e}_\gamma, \quad (9)$$

where $c^\gamma_{\alpha\beta}$ are components of the object of anholonomy. It can be shown that

$$c^\gamma_{\alpha\beta} = F_\alpha^A F_\beta^B (\partial_A F_\gamma^B - \partial_B F_\gamma^A), \quad (10)$$

where F_γ^B is the inverse of F_γ^B . The frame field $\{\mathbf{e}_\alpha\}$ defines the co-frame field $\{\vartheta^\alpha\}_{\alpha=1}^N$ such that $\vartheta^\alpha(\mathbf{e}_\beta) = \delta_\beta^\alpha$. The object of anholonomy is defined as $c^\gamma = d\vartheta^\gamma$. Writing this in the coordinate basis we have

$$c^\gamma = d(F_\gamma^B dX^B) = \sum_{\alpha < \beta} c^\gamma_{\alpha\beta} \vartheta^\alpha \wedge \vartheta^\beta. \quad (11)$$

Connection 1-forms are defined as

$$\nabla \mathbf{e}_\alpha = \mathbf{e}_\gamma \otimes \omega^\gamma_\alpha. \quad (12)$$

The corresponding connection coefficients are defined as $\nabla_{\mathbf{e}_\beta} \mathbf{e}_\alpha = \langle \omega^\gamma_\alpha, \mathbf{e}_\beta \rangle \mathbf{e}_\gamma = \omega^\gamma_{\beta\alpha} \mathbf{e}_\gamma$. In other words, $\omega^\gamma_\alpha = \omega^\gamma_{\beta\alpha} \vartheta^\beta$. Similarly, $\nabla \vartheta^\alpha = -\omega^\alpha_\gamma \vartheta^\gamma$, and $\nabla_{\mathbf{e}_\beta} \vartheta^\alpha = -\omega^\alpha_{\beta\gamma} \vartheta^\gamma$. In the non-coordinate basis torsion has the following components

$$T^\alpha_{\beta\gamma} = \omega^\alpha_{\beta\gamma} - \omega^\alpha_{\gamma\beta} + c^\alpha_{\beta\gamma}. \quad (13)$$

Similarly, the curvature tensor has the following components with respect to the frame field

$$\mathcal{R}^\alpha_{\beta\lambda\mu} = \partial_\beta \omega^\alpha_{\lambda\mu} - \partial_\lambda \omega^\alpha_{\beta\mu} + \omega^\alpha_{\beta\xi} \omega^\xi_{\lambda\mu} - \omega^\alpha_{\lambda\xi} \omega^\xi_{\beta\mu} + \omega^\alpha_{\xi\mu} c^\xi_{\beta\lambda}. \quad (14)$$

In the orthonormal frame, metric has the simple representation $\mathbf{G} = \delta_{\alpha\beta} \vartheta^\alpha \otimes \vartheta^\beta$.

2.3. Non-metricity and Weyl manifolds. Given a manifold with a metric and an affine connection $(\mathcal{B}, \nabla, \mathbf{G})$, non-metricity is a map $\mathcal{Q} : \mathcal{X}(\mathcal{B}) \times \mathcal{X}(\mathcal{B}) \times \mathcal{X}(\mathcal{B}) \rightarrow \mathcal{X}(\mathcal{B})$ defined as

$$\mathcal{Q}(\mathbf{U}, \mathbf{V}, \mathbf{W}) = \langle\langle \nabla_{\mathbf{U}} \mathbf{V}, \mathbf{W} \rangle\rangle_{\mathbf{G}} + \langle\langle \mathbf{V}, \nabla_{\mathbf{U}} \mathbf{W} \rangle\rangle_{\mathbf{G}} - \mathbf{U}[\langle\langle \mathbf{V}, \mathbf{W} \rangle\rangle_{\mathbf{G}}]. \quad (15)$$

In the frame $\{\mathbf{e}_\alpha\}$, $\mathcal{Q}_{\gamma\alpha\beta} = \mathcal{Q}(\mathbf{e}_\gamma, \mathbf{e}_\alpha, \mathbf{e}_\beta)$.² Non-metricity 1-forms are defined as $\mathcal{Q}_{\alpha\beta} = \mathcal{Q}_{\gamma\alpha\beta} \vartheta^\gamma$. It is straightforward to show that

$$\mathcal{Q}_{\gamma\alpha\beta} = \omega^\xi_{\gamma\alpha} G_{\xi\beta} + \omega^\xi_{\gamma\beta} G_{\xi\alpha} - \langle dG_{\alpha\beta}, \mathbf{e}_\gamma \rangle = \omega_{\beta\gamma\alpha} + \omega_{\alpha\gamma\beta} - \langle dG_{\alpha\beta}, \mathbf{e}_\gamma \rangle, \quad (16)$$

where d is the exterior derivative. Thus

$$\mathcal{Q}_{\alpha\beta} = \omega_{\alpha\beta} + \omega_{\beta\alpha} - dG_{\alpha\beta} =: -DG_{\alpha\beta}, \quad (17)$$

² Here, we mainly follow the notation of [22].

where D is the covariant exterior derivative. This is called *Cartan's zeroth structural equation*. For an orthonormal frame $G_{\alpha\beta} = \delta_{\alpha\beta}$ and hence

$$\mathcal{Q}_{\alpha\beta} = \omega_{\alpha\beta} + \omega_{\beta\alpha}. \quad (18)$$

Weyl 1-form is defined as

$$Q = \frac{1}{n} \mathcal{Q}_{\alpha\beta} G^{\alpha\beta}. \quad (19)$$

Thus

$$\mathcal{Q}_{\alpha\beta} = \tilde{\mathcal{Q}}_{\alpha\beta} + QG_{\alpha\beta}, \quad (20)$$

where $\tilde{\mathcal{Q}}$ is the traceless part of non-metricity. If $\tilde{\mathcal{Q}} = \mathbf{0}$, $(\mathcal{B}, \nabla, \mathbf{G})$ is called a Weyl-Cartan manifold. In addition, if ∇ is torsion-free, $(\mathcal{B}, \nabla, \mathbf{G})$ is called a Weyl manifold. It can be shown that

$$\mathcal{R}^\alpha{}_\alpha = \frac{n}{2} dQ. \quad (21)$$

This implies that for a flat Weyl manifold $dQ = 0$. One can show that [21]

$$\omega^\alpha{}_\alpha = \frac{n}{2} Q + \frac{1}{2} G^{\alpha\beta} dG_{\alpha\beta} = \frac{n}{2} Q + d \ln \sqrt{\det \mathbf{G}}. \quad (22)$$

Also

$$D\sqrt{\det \mathbf{G}} = d\sqrt{\det \mathbf{G}} - \omega^\alpha{}_\alpha \sqrt{\det \mathbf{G}} = -\frac{n}{2} Q \sqrt{\det \mathbf{G}}, \quad (23)$$

i.e. the connection ∇ is not volume-preserving.

The torsion and curvature 2-forms are defined as

$$\mathcal{T}^\alpha = d\vartheta^\alpha + \omega^\alpha{}_\beta \wedge \vartheta^\beta, \quad (24)$$

$$\mathcal{R}^\alpha{}_\beta = d\omega^\alpha{}_\beta + \omega^\alpha{}_\gamma \wedge \omega^\gamma{}_\beta. \quad (25)$$

These are called *Cartan's first and second structural equations*. In this framework, Bianchi identities then read:

$$D\mathcal{Q}_{\alpha\beta} := d\mathcal{Q}_{\alpha\beta} - \omega^\gamma{}_\alpha \wedge \mathcal{Q}_{\gamma\beta} - \omega^\gamma{}_\beta \wedge \mathcal{Q}_{\alpha\gamma} = \mathcal{R}_{\alpha\beta} + \mathcal{R}_{\beta\alpha}, \quad (26)$$

$$D\mathcal{T}^\alpha := d\mathcal{T}^\alpha + \omega^\alpha{}_\beta \wedge \mathcal{T}^\beta = \mathcal{R}^\alpha{}_\beta \wedge \vartheta^\beta, \quad (27)$$

$$D\mathcal{R}^\alpha{}_\beta := d\mathcal{R}^\alpha{}_\beta + \omega^\alpha{}_\gamma \wedge \mathcal{R}^\gamma{}_\beta - \omega^\gamma{}_\beta \wedge \mathcal{R}^\alpha{}_\gamma = 0, \quad (28)$$

where D is the covariant exterior derivative. Note that for a flat manifold $D\mathcal{T}^\alpha = 0$ and $D\mathcal{Q}_{\alpha\beta} = 0$.

2.4. The compatible volume element on a Weyl manifold. Given a Weyl manifold one needs a volume element to be able to calculate volume of an arbitrary subset. Our motivation here is to have a natural way of measuring volumes in the material manifold and hence to be able to calculate the volume density of point defects using the geometry of the Weyl material manifold. Here, by compatible volume element we mean a volume element that has vanishing covariant derivative. The volume element of the underlying Riemannian manifold is not appropriate; we need a natural volume element in the sense of [35] (see also [29]). A volume element on \mathcal{B} is a non-vanishing n -form [30]. In the orthonormal coframe field $\{\vartheta^\alpha\}$ the volume form can be written as

$$\boldsymbol{\mu} = h\vartheta^1 \wedge \dots \wedge \vartheta^n, \quad (29)$$

for some positive function h to be determined. In a coordinate chart $\{X^A\}$ the volume form is written as

$$\boldsymbol{\mu} = h\sqrt{\det \mathbf{G}} dX^1 \wedge \dots \wedge dX^n. \quad (30)$$

Divergence of an arbitrary vector field \mathbf{W} on \mathcal{B} can be defined using the Lie derivative as [1]

$$(\text{Div } \mathbf{W})\boldsymbol{\mu} = \mathcal{L}_{\mathbf{W}}\boldsymbol{\mu}. \quad (31)$$

On the other hand, divergence is also defined using the connection as

$$\text{Div}_{\nabla} \mathbf{W} = W^A{}_{|A} = W^A{}_{,A} + \Gamma^A{}_{AB}W^B. \quad (32)$$

According to Saa [35] $\boldsymbol{\mu}$ is compatible with ∇ if

$$\mathcal{L}_{\mathbf{W}}\boldsymbol{\mu} = (W^A{}_{|A})\boldsymbol{\mu}, \quad (33)$$

which is equivalent to

$$D(h\sqrt{\det \mathbf{G}}) = 0. \quad (34)$$

Using (23) we can write

$$D(h\sqrt{\det \mathbf{G}}) = hD\sqrt{\det \mathbf{G}} + \sqrt{\det \mathbf{G}} dh = \left(dh - \frac{n}{2}hQ \right) \sqrt{\det \mathbf{G}} = 0. \quad (35)$$

Thus

$$\frac{dh}{h} = d \ln h = \frac{n}{2}Q. \quad (36)$$

In coordinate form this reads

$$\frac{\partial \ln h}{\partial X^A} = \frac{n}{2}Q_A, \quad (37)$$

or

$$\frac{\partial h}{\partial X^A} - \frac{n}{2}hQ_A = 0. \quad (38)$$

Remark 1. Note that a Weylian metric on \mathcal{B} is given by the pair (\mathbf{G}, Q) with the equivalence relation $(\mathbf{G}, Q) \sim (e^A \mathbf{G}, Q - dA)$ for an arbitrary smooth function A on \mathcal{B} [15]. Now if $Q = d\Omega$ for some smooth function Ω , then by choosing $A = \Omega$ we have

$$(\mathbf{G}, Q) \sim (e^\Omega \mathbf{G}, 0). \quad (39)$$

In other words, when the Weyl 1-form is exact there exists an equivalent Riemannian manifold $(\mathcal{B}, e^\Omega \mathbf{G})$. In the equivalent Riemannian manifold the volume form is $e^{\frac{n\Omega}{2}} \mu_{\mathbf{G}}$, where $\mu_{\mathbf{G}}$ is the standard Riemannian volume form of \mathbf{G} . The volume form $e^{\frac{n\Omega}{2}} \mu_{\mathbf{G}}$ is identical to Saa's compatible volume element [35]. In this paper we call $(\mathcal{B}, e^\Omega \mathbf{G})$ and $(\mathcal{B}, \mathbf{G})$, the equivalent, and the underlying Riemannian manifolds, respectively.

3. Geometric Nonlinear Elasticity and Anelasticity

3.1. Kinematics of nonlinear elasticity. Let us first review a few of the basic notions of geometric nonlinear elasticity. A body \mathcal{B} is identified with a Riemannian manifold \mathcal{B}^3 and a configuration of \mathcal{B} is a mapping $\varphi : \mathcal{B} \rightarrow \mathcal{S}$, where \mathcal{S} is another Riemannian manifold [27, 39], where the elastic body lives (see Fig. 1a). The set of all configurations of \mathcal{B} is denoted by \mathcal{C} . A motion is a curve $c : \mathbb{R} \rightarrow \mathcal{C}; t \mapsto \varphi_t$ in \mathcal{C} . A fundamental assumption is that the body is stress-free in the material manifold. It is the geometry of these two manifolds that describes any possible residual stresses.

For a fixed t , $\varphi_t(\mathbf{X}) = \varphi(\mathbf{X}, t)$ and for a fixed \mathbf{X} , $\varphi_{\mathbf{X}}(t) = \varphi(\mathbf{X}, t)$, where \mathbf{X} is position of material points in the reference configuration \mathcal{B} . The material velocity is the map $\mathbf{V}_t : \mathcal{B} \rightarrow \varphi_t(\mathcal{B})$ given by

$$\mathbf{V}_t(\mathbf{X}) = \mathbf{V}(\mathbf{X}, t) = \frac{\partial \varphi(\mathbf{X}, t)}{\partial t} = \frac{d}{dt} \varphi_{\mathbf{X}}(t). \quad (40)$$

Similarly, the material acceleration is defined by

$$\mathbf{A}_t(\mathbf{X}) = \mathbf{A}(\mathbf{X}, t) = \frac{\partial \mathbf{V}(\mathbf{X}, t)}{\partial t} = \frac{d}{dt} \mathbf{V}_{\mathbf{X}}(t). \quad (41)$$

In components, $A^a = \frac{\partial V^a}{\partial t} + \gamma^a_{bc} V^b V^c$, where γ^a_{bc} is the Christoffel symbol of the local coordinate chart $\{x^a\}$. Note that \mathbf{A} does not depend on the connection coefficients of the material manifold. Here it is assumed that φ_t is invertible and regular. The spatial velocity of a regular motion φ_t is defined as $\mathbf{v}_t : \varphi_t(\mathcal{B}) \rightarrow \mathbb{R}^3$, $\mathbf{v}_t = \mathbf{V}_t \circ \varphi_t^{-1}$, and the spatial acceleration \mathbf{a}_t is defined as $\mathbf{a} = \dot{\mathbf{v}} = \frac{\partial \mathbf{v}}{\partial t} + \nabla_{\mathbf{v}} \mathbf{v}$. In components, $a^a = \frac{\partial v^a}{\partial t} + \frac{\partial v^a}{\partial x^b} v^b + \gamma^a_{bc} v^b v^c$.

Geometrically, deformation gradient – a central object describing deformation – is the tangent map of φ and is denoted by $\mathbf{F} = T\varphi$. Thus, at each point $\mathbf{X} \in \mathcal{B}$, it is a linear map

$$\mathbf{F}(\mathbf{X}) : T_{\mathbf{X}}\mathcal{B} \rightarrow T_{\varphi(\mathbf{X})}\mathcal{S}. \quad (42)$$

If $\{x^a\}$ and $\{X^A\}$ are local coordinate charts on \mathcal{S} and \mathcal{B} , respectively, the components of \mathbf{F} are

$$F^a_{\ A}(\mathbf{X}) = \frac{\partial \varphi^a}{\partial X^A}(\mathbf{X}). \quad (43)$$

³ This is, in general, the underlying Riemannian manifold of the material manifold.

Transpose of \mathbf{F} is defined by

$$\mathbf{F}^\top : T_{\mathbf{x}}\mathcal{S} \rightarrow T_{\mathbf{X}}\mathcal{B}, \quad \langle\langle \mathbf{F}\mathbf{V}, \mathbf{v} \rangle\rangle_{\mathbf{g}} = \langle\langle \mathbf{V}, \mathbf{F}^\top \mathbf{v} \rangle\rangle_{\mathbf{G}}, \quad (44)$$

for all $\mathbf{V} \in T_{\mathbf{X}}\mathcal{B}$, $\mathbf{v} \in T_{\mathbf{x}}\mathcal{S}$. In components, $(F^\top(\mathbf{X}))^A{}_a = g_{ab}(\mathbf{x})F^b{}_B(\mathbf{X})G^{AB}(\mathbf{X})$, where \mathbf{g} and \mathbf{G} are metric tensors on \mathcal{S} and \mathcal{B} , respectively. \mathbf{F} has the following local representation

$$\mathbf{F} = F^a{}_A \partial_a \otimes dX^A. \quad (45)$$

The right Cauchy-Green deformation tensor is defined by

$$\mathbf{C}(X) : T_{\mathbf{X}}\mathcal{B} \rightarrow T_{\mathbf{X}}\mathcal{B}, \quad \mathbf{C}(\mathbf{X}) = \mathbf{F}^\top(\mathbf{X})\mathbf{F}(\mathbf{X}). \quad (46)$$

In components, $C^A{}_B = (F^\top)^A{}_a F^a{}_B$. It is straightforward to show that \mathbf{C}^b is the pull-back of the spatial metric, i.e.

$$\mathbf{C}^b = \varphi^* \mathbf{g} = \mathbf{F}^* \mathbf{g} \mathbf{F}, \text{ i.e. } C_{AB} = (g_{ab} \circ \varphi) F^a{}_A F^b{}_B. \quad (47)$$

3.2. Material manifold and anelasticity. In classical elasticity one starts with a stress-free configuration embedded in the ambient space and then makes this embedding time-dependent (a motion). In anelastic problems (anelastic in the sense of Eckart [11]), the stress-free configuration is another manifold with a geometry explicitly depending on the anelasticity source(s), see Fig. 1b. The ambient space being a Riemannian manifold $(\mathcal{S}, \mathbf{g})$, the computation of stresses requires a Riemannian material manifold $(\mathcal{B}, \mathbf{G})$ (the underlying Riemannian material manifold) and a map $\varphi : \mathcal{B} \rightarrow \mathcal{S}$. For example, in the case of non-uniform temperature changes and bulk growth [32, 40] one starts with a material metric \mathbf{G} that specifies the relaxed distances of the material points. However, the material metric cannot always be obtained directly.

It turns out that for defects in solids, a metric-affine manifold can describe the stress-free configuration of the body. In the case of dislocations, the material connection is flat, metric-compatible, and has a non-vanishing torsion, which is identified with the dislocation density tensor, i.e. the material manifold is a Weitzenböck manifold [41]. Given a dislocation density tensor one can obtain the torsion of the affine connection. Then using Cartan's moving frames and structural equations one can find an orthonormal frame compatible with the torsion tensor. This, in turn, provides the material metric. Then, the computation of stress amounts to find a mapping from the underlying Riemannian material manifold to the ambient space manifold. In the case of disclinations, the physically relevant object is the curvature of a torsion-free and metric-compatible connection and one can again find the metric using Cartan's structural equations [42].

For a solid with distributed point defects the material manifold is a Weyl manifold. Point defects affect the volume of the stress-free configuration and this can be described using non-metricity as will be shown shortly. The metric is obtained using Cartan's structural equations and the compatible volume element of the Weyl material manifold. We conclude that all anelastic effects can be embedded in the appropriate geometric characterization of the material manifold on which the computation of stresses reduces to a classical elasticity problem. This means that, in particular, the deformation gradient by construction is purely elastic.

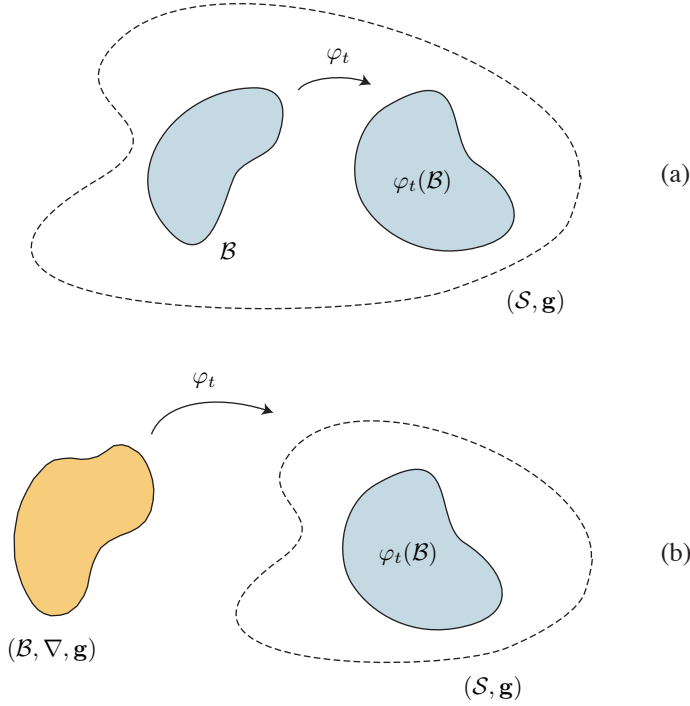


Fig. 1. (a) Kinematics of nonlinear elasticity. Reference configuration is a submanifold of the ambient space manifold. The material metric is the induced submanifold metric. (b) Kinematics of nonlinear anelasticity. Material manifold is a metric-affine manifold $(\mathcal{B}, \nabla, \mathbf{G})$. Motion is a time-dependent mapping from the underlying Riemannian material manifold $(\mathcal{B}, \mathbf{G})$ into the Riemannian ambient space manifold $(\mathcal{S}, \mathbf{g})$.

3.3. Equations of motion. The internal energy density E (or free energy density Ψ) of a solid depends on the deformation gradient \mathbf{F} . Since a scalar function of a two-point tensor must explicitly depend on both \mathbf{G} and \mathbf{g} , we have

$$E = E(\mathbf{X}, \mathbf{N}, \Theta, \mathbf{F}, \mathbf{G}, \mathbf{g}), \quad \Psi = \Psi(\mathbf{X}, \Theta, \mathbf{F}, \mathbf{G}, \mathbf{g}), \quad (48)$$

where \mathbf{N} and Θ are the specific entropy and absolute temperature, respectively.

One can derive the equations of motion by either using an action principle or using covariance of energy balance [27, 43]. For a motion $\varphi : \mathcal{B} \rightarrow \mathcal{S}$, where $(\mathcal{B}, \mathbf{G})$ and $(\mathcal{S}, \mathbf{g})$ are, respectively, the (underlying) Riemannian material and ambient space manifolds, the governing equations obtained as a consequence of the conservation of mass and balance of linear and angular momenta, in material form read

$$\frac{\partial \rho_0}{\partial t} = 0, \quad \text{Div } \mathbf{P} + \rho_0 \mathbf{B} = \rho_0 \mathbf{A}, \quad \mathbf{P} \mathbf{F}^\top = \mathbf{F} \mathbf{P}^\top, \quad (49)$$

where ρ_0 , \mathbf{P} , \mathbf{B} , and \mathbf{A} are the material mass density, the first Piola-Kirchhoff stress, the body force per unit undeformed volume (calculated using the Riemannian volume form), and the material acceleration, respectively. In components,

the Cauchy equation (49)₂ reads

$$\frac{\partial P^{aA}}{\partial X^A} + \Gamma^A_{AB} P^{aB} + \gamma^a_{bc} F^b_A P^{cA} + \rho_0 B^a = \rho_0 A^a, \quad (50)$$

where Γ^A_{BC} are the Christoffel symbols of the material metric. Equivalently, in spatial coordinates

$$\mathbf{L}_v \rho = 0, \quad \operatorname{div} \boldsymbol{\sigma} + \rho \mathbf{b} = \rho \mathbf{a}, \quad \boldsymbol{\sigma}^T = \boldsymbol{\sigma}, \quad (51)$$

where ρ , $\boldsymbol{\sigma}$, \mathbf{b} , and \mathbf{a} are the spatial mass density, Cauchy stress, body force per unit deformed volume, and spatial acceleration, respectively. $\mathbf{L}_v \rho$ is the Lie derivative of the mass density with respect to the (time-dependent) spatial velocity. Note that $\sigma^{ab} = \frac{1}{J} P^{aA} F^b_A$, where $J = \sqrt{\frac{\det \mathbf{g}}{\det \mathbf{G}}} \det \mathbf{F}$ is the Jacobian.

4. Residual Stress Field of a Spherically-Symmetric Distribution of Point Defects

As an application of the geometric theory, we revisit a classical problem of linear elasticity in the general framework of exact nonlinear elasticity. Namely, we construct the material manifold of a spherically-symmetric distribution of point defects in a ball of radius R_o , which is traction-free on its boundary sphere. The Weyl material manifold is then used to calculate the residual stress field.

4.1. The Weyl material manifold. In order to find a solution, we follow the procedure in [3, 41] and start by an ansatz for the coframe field. We then find a flat connection, which is torsion-free but has a non-vanishing non-metricity compatible with the given point defect distribution. We do this using Cartan's structural equations and the compatible volume form of the Weyl material manifold. In the spherical coordinates (R, Θ, Φ) , $R \geq 0$, $0 \leq \Theta \leq \pi$, $0 \leq \Phi < 2\pi$, let us look for a coframe field of the following form⁴

$$\vartheta^1 = f(R) dR, \quad \vartheta^2 = R d\Theta, \quad \vartheta^3 = R \sin \Theta d\Phi, \quad (52)$$

for some unknown function f to be determined. We choose the following connection 1-forms

$$\boldsymbol{\omega} = [\omega^\alpha_\beta] = \begin{pmatrix} \omega^1_1 & \omega^1_2 & -\omega^3_1 \\ -\omega^1_2 & \omega^2_2 & \omega^2_3 \\ \omega^3_1 & -\omega^2_3 & \omega^3_3 \end{pmatrix}, \quad (53)$$

where

$$\omega^1_2 = -\frac{1}{R} \vartheta^2, \quad \omega^2_3 = -\frac{\cot \Theta}{R} \vartheta^3, \quad \omega^3_1 = \frac{1}{R} \vartheta^3, \quad \omega^1_1 = \omega^2_2 = \omega^3_3 = q(R) \vartheta^1, \quad (54)$$

for a function q to be determined. This means that

$$\mathcal{Q}_{\alpha\beta} = 2\delta_{\alpha\beta} q(R) \vartheta^1. \quad (55)$$

⁴ This construction is similar to that of [3]. Note that the Riemannian volume element is $\mu_{\mathbf{G}} = \vartheta^1 \wedge \vartheta^2 \wedge \vartheta^3 = R^2 f(R) \sin \Theta dR \wedge d\Theta \wedge d\Phi$, and hence $f(R) > 0$.

We now need to enforce $\mathcal{T}^\alpha = 0$. Note that

$$d\vartheta^1 = 0, \quad d\vartheta^2 = \frac{1}{Rf(R)}\vartheta^1 \wedge \vartheta^2, \quad d\vartheta^3 = -\frac{1}{Rf(R)}\vartheta^3 \wedge \vartheta^1 + \frac{\cot \Theta}{R}\vartheta^2 \wedge \vartheta^3. \quad (56)$$

From Cartan's first structural equations we obtain

$$\begin{aligned} \mathcal{T}^1 &= 0, \quad \mathcal{T}^2 = \left[\frac{1}{Rf(R)} - \frac{1}{R} + q(R) \right] \vartheta^1 \wedge \vartheta^2, \\ \mathcal{T}^3 &= \left[\frac{1}{Rf(R)} - \frac{1}{R} + q(R) \right] \vartheta^3 \wedge \vartheta^1. \end{aligned} \quad (57)$$

Therefore

$$q(R) = \frac{1}{R} \left[1 - \frac{1}{f(R)} \right]. \quad (58)$$

It can be checked that for these connection 1-forms $\mathcal{R}^\alpha{}_\beta = 0$ are trivially satisfied. In this example the Weyl 1-form is written as

$$Q = 2q(R)\vartheta^1 = \frac{2}{R} \left[1 - \frac{1}{f(R)} \right] \vartheta^1 = \frac{2(f(R) - 1)}{R} dR. \quad (59)$$

It is seen that $dQ = 0$ as is expected for a flat Weyl manifold.

4.2. Volume density of point defects. Consider a spherical shell of radius R and thickness ΔR . In the absence of point defects (Euclidean material manifold), the volume of this shell is

$$\Delta V_0 = 2\pi \int_0^\pi \sin \Theta \, d\Theta \int_R^{R+\Delta R} \xi^2 d\xi = 4\pi \int_R^{R+\Delta R} \xi^2 d\xi. \quad (60)$$

Now in the underlying Riemannian material manifold, the volume of the same spherical shell with point defects is

$$\Delta V_{\text{Riemannian}} = 2\pi \int_0^\pi \sin \Theta \, d\Theta \int_R^{R+\Delta R} \xi^2 f(\xi) d\xi = 4\pi \int_R^{R+\Delta R} \xi^2 f(\xi) d\xi. \quad (61)$$

If there are only vacancies in this spherical shell (and no interstitials) we expect the volume of the Riemannian material manifold to be smaller than ΔV_0 . In other words, for a distribution of vacancies we expect $0 < f(R) < 1$.

In the presence of point defects the compatible volume element in the Weyl material manifold is written as

$$\boldsymbol{\mu} = h(R)\vartheta^1 \wedge \vartheta^2 \wedge \vartheta^3 = R^2 f(R)h(R) \sin \Phi \, dR \wedge d\Theta \wedge d\Phi, \quad (62)$$

for some positive function h satisfying (37). In the Weyl material manifold the volume of the spherical shell of radius R and thickness ΔR is⁵

$$\Delta V = 2\pi \int_0^\pi \sin \Theta \, d\Theta \int_R^{R+\Delta R} \xi^2 f(\xi)h(\xi) d\xi = 4\pi \int_R^{R+\Delta R} \xi^2 f(\xi)h(\xi) d\xi. \quad (63)$$

⁵ Note that for the case of a spherically-symmetric point defect distribution as a consequence of the Poincaré Lemma, $Q = d\Omega$ (see Remark 1). In other words, we are calculating the volume of the equivalent Riemannian manifold of the Weyl material manifold.

Total volume of the defects in the spherical shell is $\Delta V_d = \Delta V_0 - \Delta V$. Thus

$$\Delta V_d = 4\pi \int_R^{R+\Delta R} \xi^2 [1 - f(\xi)h(\xi)] d\xi. \quad (64)$$

The volume density of point defects is defined as⁶

$$n(R) = \lim_{\Delta R \rightarrow 0} \frac{\Delta V_d}{\Delta V_0} = \lim_{\Delta R \rightarrow 0} \frac{4\pi \int_R^{R+\Delta R} \xi^2 [1 - f(\xi)h(\xi)] d\xi}{4\pi R^2 \Delta R} = 1 - f(R)h(R). \quad (65)$$

Therefore

$$f(R) = \frac{1 - n(R)}{h(R)}. \quad (66)$$

Note that $f(R) > 0$ and $h(R) > 0$ imply that

$$n(R) < 1. \quad (67)$$

For our spherically-symmetric point defect distribution, the relationship (37) is simplified to read

$$\frac{d}{dR} \ln h(R) = \frac{h'(R)}{h(R)} = \frac{3(f(R) - 1)}{R}. \quad (68)$$

From (66) and (68) we obtain

$$Rh'(R) + 3h(R) = 3(1 - n(R)). \quad (69)$$

Hence

$$h(R) = 1 - \frac{1}{R^3} \int_0^R 3y^2 n(y) dy. \quad (70)$$

Therefore

$$f(R) = \frac{1 - n(R)}{1 - \frac{1}{R^3} \int_0^R 3y^2 n(y) dy}. \quad (71)$$

To check for consistency, let us consider a spherically-symmetric distribution of vacancies in a ball of radius R_0 such that $n(R) < 0$ ($h(R) > 1$) and $n'(R) > 0$. For a distributed vacancy, we expect a smaller relaxed volume, i.e. $\mu_0 > \mu_{\mathbf{G}}$ and hence $f(R) < 1$, where μ_0 and $\mu_{\mathbf{G}}$ are the volume forms of the flat Euclidean manifold and the underlying Riemannian manifold, respectively. This can easily be verified using (71).

Example 1. If $n(R) = n_0$, then $f(R) = 1$.

Remark 2. For an arbitrary distribution of point defects the defective solid is stress-free in a Weyl manifold $(\mathcal{B}, \mathbf{G}, Q)$. Let us denote the volume form of the Weyl manifold by μ . For a subbody $\mathcal{U} \subset \mathcal{B}$, the volume of the virgin (defect-free) and the defective subbody are

$$V_0(\mathcal{U}) = \int_{\mathcal{U}} \mu_0, \quad V(\mathcal{U}) = \int_{\mathcal{U}} \mu. \quad (72)$$

The volume of the point defects in \mathcal{U} is calculated as

$$V_d(\mathcal{U}) = \int_{\mathcal{U}} \mu_0 - \int_{\mathcal{U}} \mu = \int_{\mathcal{U}} (\mu_0 - \mu) = \int_{\mathcal{U}} n\mu_0. \quad (73)$$

This implies that n is the volume density of the point defects. Note that for vacancies $V_d < 0$.

⁶ For a distribution of vacancies $n(R) < 0$ and for a distribution of interstitials $n(R) > 0$.

4.3. *Residual stress calculation.* The material metric in spherical coordinates (R, Θ, Φ) has the following form:

$$\mathbf{G} = \begin{pmatrix} f^2(R) & 0 & 0 \\ 0 & R^2 & 0 \\ 0 & 0 & R^2 \sin^2 \Theta \end{pmatrix}. \quad (74)$$

We use the spherical coordinates (r, θ, ϕ) for the Euclidean ambient space with the following metric.

$$\mathbf{g} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & r^2 & 0 \\ 0 & 0 & r^2 \sin^2 \theta \end{pmatrix}. \quad (75)$$

In order to obtain the residual stress field we embed the material manifold into the ambient space. We look for solutions of the form $(r, \theta, \phi) = (r(R), \Theta, \Phi)$, and hence $\det \mathbf{F} = r'(R)$. Assuming an incompressible solid, we have

$$J = \sqrt{\frac{\det \mathbf{g}}{\det \mathbf{G}}} \det \mathbf{F} = \frac{r^2(R)}{R^2 f(R)} r'(R) = 1. \quad (76)$$

Assuming that $r(0) = 0$ this gives us

$$r(R) = \left(\int_0^R 3\xi^2 f(\xi) d\xi \right)^{\frac{1}{3}}. \quad (77)$$

For a neo-Hookean material we have $P^{aA} = \mu F^a{}_B G^{AB} - p(F^{-1})^A{}_b g^{ab}$, where $p = p(R)$ is the pressure field. Thus

$$\mathbf{P} = \begin{pmatrix} \frac{\mu R^2}{f(R)r^2(R)} - \frac{p(R)r^2(R)}{f(R)R^2} & 0 & 0 \\ 0 & \frac{\mu}{R^2} - \frac{p(R)}{r^2(R)} & 0 \\ 0 & 0 & \frac{\mu}{R^2 \sin^2 \Theta} - \frac{p(R)}{r(R)^2 \sin^2 \Theta} \end{pmatrix}. \quad (78)$$

Hence

$$\boldsymbol{\sigma} = \begin{pmatrix} \frac{\mu R^4}{r^4(R)} - p(R) & 0 & 0 \\ 0 & \frac{\mu}{R^2} - \frac{p(R)}{r^2(R)} & 0 \\ 0 & 0 & \frac{1}{\sin^2 \Theta} \left[\frac{\mu}{R^2} - \frac{p(R)}{r^2(R)} \right] \end{pmatrix}. \quad (79)$$

In the absence of body forces, the only non-trivial equilibrium equation is $\sigma^{ra}|_a = 0$ ($p = p(R)$ is the consequence of the other two equilibrium equations), which is simplified to read

$$\sigma^{rr}{}_{,r} + \frac{2}{r} \sigma^{rr} - r \sigma^{\theta\theta} - r \sin^2 \theta \sigma^{\phi\phi} = 0. \quad (80)$$

Or

$$\frac{r^2}{R^2 f} \sigma^{rr}{}_{,R} + \frac{2}{r} \sigma^{rr} - 2r \sigma^{\theta\theta} = 0. \quad (81)$$

This then gives us

$$p'(R) = -\frac{2\mu}{r(R)} \left[f(R) \left(\frac{R}{r(R)} \right)^6 - 2 \left(\frac{R}{r(R)} \right)^3 + f(R) \right]. \quad (82)$$

Let us assume that the defective body is a ball of radius R_o . Assuming that the boundary of the ball is traction-free ($\sigma^{rr}(R_o) = 0$) we obtain

$$p(R_o) = \mu \frac{R_o^4}{r^4(R_o)}. \quad (83)$$

Therefore, the pressure at all points inside the ball is

$$p(R) = \mu \frac{R_o^4}{r^4(R_o)} + 2\mu \int_R^{R_o} \left[f(\xi) \frac{\xi^6}{r^7(\xi)} - 2 \frac{\xi^3}{r^4(\xi)} + \frac{f(\xi)}{r(\xi)} \right] d\xi, \quad (84)$$

and the radial stress is

$$\begin{aligned} \sigma^{rr}(R) = & -2\mu \int_R^{R_o} \left[f(\xi) \frac{\xi^6}{r^7(\xi)} - 2 \frac{\xi^3}{r^4(\xi)} + \frac{f(\xi)}{r(\xi)} \right] d\xi \\ & + \mu \left[\frac{R^4}{r^4(R)} - \frac{R_o^4}{r^4(R_o)} \right]. \end{aligned} \quad (85)$$

For a given point defect distribution $n(R)$, $f(R)$ is obtained using (71). Pressure and stress are then obtained by substituting $f(R)$ into (84) and (85), respectively.

Remark 3. When $n(R) = n_0$, we saw that $f(R) = 1$. This then implies that $r(R) = R$ and $p(R) = \mu$, i.e. this point defect distribution is stress-free. Eshelby [12] showed this in the linearized setting. We will show in §4.4 that this is the only zero-stress spherically-symmetric point defect distribution.

Example 2. Let us consider the following point defect distribution⁷

$$n(R) = \begin{cases} n_0 & 0 \leq R \leq R_i, \\ 0 & R > R_i, \end{cases} \quad (86)$$

where $R_i < R_o$. Thus

$$0 \leq R \leq R_i : f(R) = 1, \quad (87)$$

$$R > R_i : f(R) = \frac{1}{1 - n_0 \left(\frac{R_i}{R} \right)^3}. \quad (88)$$

Also

$$0 \leq R \leq R_i : r(R) = R, \quad (89)$$

$$R > R_i : r(R) = \left[R^3 + n_0 R_i^3 \ln \left(\frac{(R/R_i)^3 - n_0}{1 - n_0} \right) \right]^{\frac{1}{3}}. \quad (90)$$

⁷ Note that the total volume of point defects is $(\frac{4\pi}{3} R_i^3) n_0$.

Note that for $0 \leq R \leq R_i$:

$$p(R) = \mu \frac{R_o^4}{r^4(R_o)} + 2\mu \int_{R_i}^{R_o} \left[f(\xi) \frac{\xi^6}{r^7(\xi)} - 2 \frac{\xi^3}{r^4(\xi)} + \frac{f(\xi)}{r(\xi)} \right] d\xi = p_i, \quad (91)$$

i.e. pressure is uniform and consequently $\sigma^{rr} = \mu - p_i$ is uniform. Fig. 2 shows the distribution of P^{rR} in the interval $[R_i, R_o]$ for different vacancy distributions and when $R_o = 10R_i$.

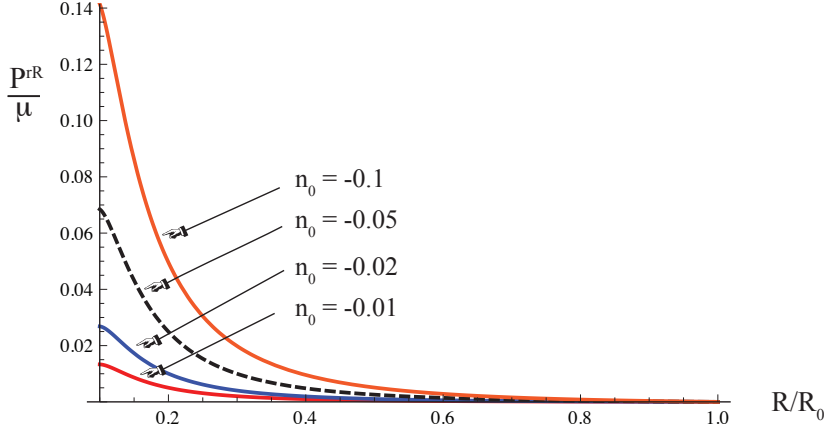


Fig. 2. P^{rR} distributions for different values of n_0 and $R_i = R_o/10$.

Remark 4. The other two stress components are also equal to $\mu - p_i$ in the ball $R \leq R_i$. To see this, note that in curvilinear coordinates, the components of a tensor may not have the same physical dimensions. The following relation holds between the Cauchy stress components (unbarred) and its physical components (barred) [38]

$$\bar{\sigma}^{ab} = \sigma^{ab} \sqrt{g_{aa}g_{bb}} \quad \text{no summation on } a \text{ or } b. \quad (92)$$

The spatial metric in spherical coordinates has the form $\text{diag}(1, r^2, r^2 \sin^2 \theta)$, and this means that the nonzero Cauchy stress components are

$$\begin{aligned} \bar{\sigma}^{rr} = \sigma^{rr} &= \mu \frac{R^4}{r^4(R)} - p(R), & \bar{\sigma}^{\theta\theta} = r^2 \sigma^{\theta\theta} &= \mu \frac{r^2(R)}{R^2} - p(R), \\ \bar{\sigma}^{\phi\phi} = r^2 \sin^2 \theta \sigma^{\phi\phi} &= \mu \frac{r^2(R)}{R^2} - p(R). \end{aligned} \quad (93)$$

It follows that inside the sphere of radius R_i both $\bar{\sigma}^{\theta\theta}$ and $\bar{\sigma}^{\phi\phi}$ are equal to $\mu - p_i$. Thinking of the ball $R \leq R_i$ as an inclusion, this is the nonlinear analogue of Eshelby's celebrated inclusion problem [13]. This result also holds for an arbitrary nonlinear isotropic incompressible solid as shown next.

Now let us assume that the body is isotropic and incompressible (not necessarily neo-Hookean). The second Piola-Kirchhoff stress tensor has the following representation [27]

$$S_{AB} = \alpha_0 G_{AB} + \alpha_1 C_{AB} + \alpha_2 C_A^D C_{DB}, \quad (94)$$

where α_0, α_1 , and α_2 are functions of position and invariants of \mathbf{C} . For $R \leq R_i$, $C_{AB} = \delta_{AB}$ and hence $S_{AB} = \alpha \delta_{AB}$, where $\alpha = \alpha_0 + \alpha_1 + \alpha_2$ is a constant for a homogeneous solid. This means that similar to the neo-Hookean solid $P^{aA} = (\alpha - p(R))\delta^{aA}$. Equilibrium equations dictate $p(R) = \alpha$, and hence we have proved the following proposition.

Proposition 1. *For a homogenous spherical ball of radius R_o made of an isotropic and incompressible solid, traction-free on its boundary sphere, and with the following point defect distribution*

$$n(R) = \begin{cases} n_0 & 0 \leq R \leq R_i, \\ 0 & R_i < R \leq R_o, \end{cases} \quad (95)$$

in the ball $R \leq R_i$, the stress is uniform and hydrostatic.

4.4. Zero-stress spherically-symmetric point defect distributions. Next we identify all spherically-symmetric point defect distributions that are zero-stress. This is equivalent to the underlying Riemannian material manifold being flat (in the case of simply-connected material manifolds). Given the coframe field (52) using Cartan's first structural equations its Levi-Civita connections are obtained as

$$\bar{\omega}^1{}_2 = -\frac{1}{Rf(R)}\vartheta^2, \quad \bar{\omega}^2{}_3 = -\frac{\cot \Theta}{R}\vartheta^3, \quad \bar{\omega}^3{}_1 = \frac{1}{Rf(R)}\vartheta^3. \quad (96)$$

Using Cartan's second structural equations we obtain the following Levi-Civita curvature 2-forms

$$\begin{aligned} \bar{\mathcal{R}}^1{}_2 &= \frac{f'(R)}{Rf^3(R)}\vartheta^1 \wedge \vartheta^2, & \bar{\mathcal{R}}^2{}_3 &= -\frac{1}{R^2} \left(1 - \frac{1}{f^2(R)} \right) \vartheta^2 \wedge \vartheta^3, \\ \bar{\mathcal{R}}^3{}_1 &= \frac{f'(R)}{Rf^3(R)}\vartheta^3 \wedge \vartheta^1. \end{aligned} \quad (97)$$

The Riemannian material manifold is flat if and only if $f'(R) = 0$ and $f^2(R) = 1$. This means that $f(R) = 1$ is the only possibility. From (71) we see that the zero-stress point defect distributions must satisfy the following integral equation

$$R^3 n(R) = \int_0^R 3y^2 n(y) dy \quad \forall R \geq 0. \quad (98)$$

Taking derivatives of both sides we obtain $n'(R) = 0$ or $n(R) = n_0$.

4.5. *Comparison with the classical linear solution.* Here we compare our nonlinear solution with the classical linearized elasticity solution. For an incompressible linear elastic material with a single point defect at the origin recall that [37]

$$\sigma^{rr} = -\frac{4\mu C}{R^3} \left(1 - \frac{R^3}{R_o^3}\right), \quad \sigma^{\theta\theta} = \sigma^{\phi\phi} = \frac{2\mu C}{R^3} \left(1 + \frac{2R^3}{R_o^3}\right), \quad (99)$$

where

$$C = \frac{\delta v}{4\pi}, \quad (100)$$

and δv being the volume change due to the point defect. To compare our nonlinear solution with this classical solution we note that

$$\delta v = \frac{4\pi}{3} R_i^3 n_0. \quad (101)$$

Therefore

$$C = \frac{1}{3} R_i^3 n_0. \quad (102)$$

While an exact analytic solution is not available, an asymptotic expansion for R_i small gives

$$\sigma^{rr} = -\frac{4\mu C}{R^3} \left\{ \left(1 - \frac{R^3}{R_o^3}\right) \left[1 + \log \left(\frac{R_o^3}{R_i^3(1-n_0)} \right) \right] + \log \left(\frac{R^3}{R_o^3} \right) \right\} + O(R_i^6), \quad (103)$$

valid for $R_i \leq R \leq R_o$. We see that the linear solution is modified by a geometric factor $\log(R_o^3/(R_i^3(1-n_0)))$ and a nonlinear logarithmic correction. As can be seen in Fig. 3, the two solutions are very close and the classical linear solution captures most of the features of the nonlinear solution but it diverges at the origin and systematically underestimates the stress outside the core of the defect. By comparison, the nonlinear solution is regular over the entire domain. The nonlinear analysis of a continuous distribution of point defects in a small core provides an effective way of regularizing the solution for the stress. This is particularly important in deriving estimates for fracture and plastic yielding.

Acknowledgements. This publication was based on work supported in part by Award No KUK C1-013-04, made by King Abdullah University of Science and Technology (KAUST). AG is a Wolfson Royal Society Merit Holder. AY was partially supported by AFOSR – Grant No. FA9550-10-1-0378 and NSF – Grant No. CMMI 1130856.

References

1. Abraham, R., J.E. Marsden and T. Ratiu [1988], *Manifolds, Tensor Analysis, and Applications*, Springer-Verlag, New York.
2. Acharya, A. [2001], A model of crystal plasticity based on the theory of continuously distributed dislocations. *Journal of the Mechanics and Physics of Solids* **49**:761-784.
3. Adak, M. and Sert, O. [2005], A solution to symmetric teleparallel gravity. *Turkish Journal of Physics* **29**:1-7.
4. Bilby, B. A., R., Bullough, and E., Smith [1955], Continuous distributions of dislocations: a new application of the methods of non-Riemannian geometry. *Proceedings of the Royal Society of London* **A231**(1185):263-273.
5. Bilby, B. A., and E., Smith [1956], Continuous distributions of dislocations. III. *Proceedings of the Royal Society of London* **A236**(1207): 481-505.

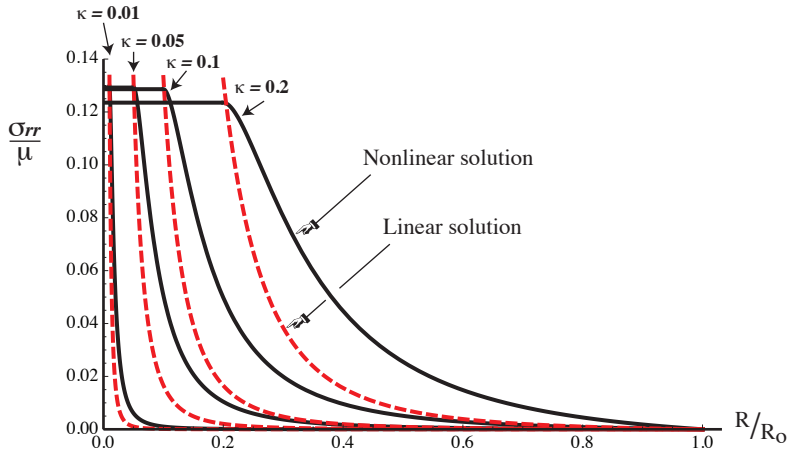


Fig. 3. Comparison of the linear (dashed) and nonlinear (solid) solutions for the radial stress distribution for different values of $\kappa = R_i/R_o$ and $n_0 = -0.1$.

6. Bochner, S. and Yano, K. [1952], Tensor-fields in non-symmetric connections. *Annals of Mathematics* **56**(3):504-519.
7. Cartan, E. [1924], Sur les variétés à connexion affine et la théorie de la relativité généralisée (première partie suite). *Annales Scientifiques de l'Ecole Normale Supérieure* **41**:1-25.
8. Cartan, E. [1995], *On Manifolds with an Affine Connection and the Theory of General Relativity*. Bibliopolis, Napoli.
9. Cartan, E. [2001], *Riemannian Geometry in an Orthogonal Frame*. World Scientific, New Jersey.
10. de Wit, R. [1981], A view of the relation between the continuum theory of lattice defects and non-Euclidean geometry in the linear approximation. *International Journal of Engineering Science* **19**(12):1475-1506.
11. Eckart, C. [1948], The thermodynamics of irreversible processes. 4. The theory of elasticity and anelasticity. *Physical Review* **73**(4):373-382.
12. Eshelby, J.D. [1954], Distortion of a crystal by point imperfections. *Journal of Applied Physics* **25**(2):255-261.
13. Eshelby, J.D. [1957], The determination of the elastic field of an ellipsoidal inclusion, and related problems. *Proceedings of the Royal Society of London Series A-Mathematical and Physical Sciences* **241**(1226):376-396.
14. Falk, F. [1981], Theory of elasticity of coherent inclusions by means of non-metric geometry. *Journal of Elasticity* **11**(4):359-372.
15. Folland, G.B. [1970], Weyl manifolds. *Journal of Differential Geometry* **4**:145-153.
16. Garikipati, K., M. Falk, et al. [2006], The continuum elastic and atomistic viewpoints on the formation volume and strain energy of a point defect. *Journal of the Mechanics and Physics of Solids* **54**(9):1929-1951.
17. Gilkey, P., S. Nikčević [2011], Geometric realizations, curvature decompositions, and Weyl manifolds. *Journal of Geometry and Physics* **61**(1):270-275.
18. Grachev, A.V., A. I. Nesterov, et al. [1989], The gauge theory of point defects. *Physica Status Solidi (b)* **156**(2):403-410.
19. Gordeeva, I.A., Pan'zhenskii, V.I., and Stepanov, S.E. [2010], Riemann-Cartan manifolds. *Journal of Mathematical Sciences* **169**(3):342-361.
20. Hehl, F. W., E. A. Lord, L. L Smalley [1981], Metric-affine variational principles in general relativity II. Relaxation of the Riemannian constraint. *General Relativity and Gravitation* **13**(11):1037-1056.
21. Hehl, F. W., J. D. McCrea, E.W. Mielke, and Y. Ee'man [1995], Metric-affine gauge-theory of gravity: field equations, Noether identities, World spinors, and breaking of dilation invariance. *Physics Reports* **258**(1-2):1-171.

22. Hehl, F. W. and Y. N. Obukhov [1983], *Foundations of Classical Electrodynamics Charge, Flux, and Metric*. Birkhäuser, Boston.
23. Kondo, K. [1955], Geometry of elastic deformation and incompatibility, *Memoirs of the Unifying Study of the Basic Problems in Engineering Science by Means of Geometry*, (K. Kondo, ed.), vol. 1, Division C, Gakujutsu Bunken Fukyo-Kai, 1955, pp. 5-17.
24. Kondo, K. [1955], Non-Riemannian geometry of imperfect crystals from a macroscopic viewpoint, *Memoirs of the Unifying Study of the Basic Problems in Engineering Science by Means of Geometry*, (K. Kondo, ed.), vol. 1, Division D-I, Gakujutsu Bunken Fukyo-Kai, 1955, pp. 6-17
25. Kröner, E. [1990], The differential geometry of elementary point and line defects in Bravais crystals. *International Journal of Theoretical Physics* **29**(11):1219-1237.
26. Love, A.H. [1924], *Mathematical Theory of Elasticity*. Cambridge University Press, Cambridge.
27. Marsden, J.E. and T.J.R. Hughes [1983], *Mathematical Foundations of Elasticity*. Dover, New York.
28. Miri, M and N., Rivier [2002], Continuum elasticity with topological defects, including dislocations and extra-matter. *Journal of Physics A - Mathematical and General* **35**:1727-1739.
29. Mosna, R.A. and Saa, A. [2005], Volume elements and torsion. *Journal of Mathematical Physics* **46**:112502;1-10.
30. Nakahara, M. [2003], *Geometry, Topology and Physics*. Taylor & Francis, New York.
31. Nester, J. M., [2010] Normal frames for general connections. *Annalen der Physik* **19**(1-2):45-52.
32. Ozakin, A. and A. Yavari [2010], A geometric theory of thermal stresses, *Journal of Mathematical Physics* **51**:032902, 1-32.
33. Rosakis, P. and Rosakis, A. J. [1988], The screw dislocation problem in incompressible finite elastostatics - a discussion of nonlinear effects. *Journal of Elasticity* **20**(1):3-40.
34. Rosen, N. [1982], Weyl's geometry and physics. *Foundations of Physics* **12**(3):213-248.
35. Saa, A. [1995], Volume-forms and minimal action principles in affine manifolds. *Journal of Geometry and Physics* **15**:102-108.
36. Schouten, J.A. [1926], *Ricci-Calculus: An Introduction to Tensor Analysis and its Geometrical Applications*, Springer-Verlag, Berlin.
37. Teodosiu, C. [1982], *Elastic Models of Crystal Defects*. Springer-Verlag, Berlin.
38. Truesdell, C. [1953], The physical components of vectors and tensors. *ZAMM* **33**:345-356.
39. Yavari, A., J. E. Marsden and M. Ortiz [2006], On the spatial and material covariant balance laws in elasticity. *Journal of Mathematical Physics* **47**:042903;85-112.
40. Yavari, A. [2010] A geometric theory of growth mechanics. *Journal of Nonlinear Science* **20**(6):781-830.
41. Yavari, A. and A. Goriely [2012] Riemann-Cartan geometry of nonlinear dislocation mechanics. *Archive for Rational Mechanics and Analysis*, 10.1007/s00205-012-0500-0.
42. Yavari, A. and A. Goriely [2012] Riemann-Cartan geometry of nonlinear disclination mechanics. *Mathematics and Mechanics of Solids*, to appear.
43. Yavari, A. and J.E. Marsden [2012] Covariantization of nonlinear elasticity. *Zeitschrift für Angewandte Mathematik und Physik (ZAMP)*, doi: 10.1007/s00033-011-0191-7.
44. Zubov, L.M. [1997], *Nonlinear Theory of Dislocations and Disclinations in Elastic Bodies*. Springer, Berlin.

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