Title
Skin friction blistering: computer model.

Journal
Skin research and technology : official journal of International Society for Bioengineering and the Skin (ISBS) [and] International Society for Digital Imaging of Skin (ISDIS) [and] International Society for Skin Imaging (ISSI), 13(3)

ISSN
0909-752X

Authors
Xing, Malcolm
Pan, Ning
Zhong, Wen
et al.

Publication Date
2007-08-01

Peer reviewed

Numerical Model of Skin Frictional Blistering

Malcolm Xing and Ning Pan, Ph.D
Department of Biological System Engineering
University of California, Davis, CA95616, USA

Wen Zhong, Ph.D
Department of Medical Microbiology and Department of Textile Sciences,
University of Manitoba, Winnipeg, MB R3T 2N2 Canada

Howard Maibach, MD
Department of Dermatology
University of California, San Francisco, CA 94143-0989, USA

Background/purpose

Friction blisters, a common injury in sports and military operations, can adversely effect or even halt performance. Given its frequency and hazardous nature, recent research efforts have been limited. Blistering can be treated as a delamination phenomenon; similar issues in materials science have been extensively investigated in theory and in experiment. In studying blistering, one obstacle is the difficulty of conducting experiment on man and animals. Computer modeling thus becomes a preferred tool.

Method

This paper employed a dynamic non-linear finite element model with a blister-characterized structure and contact algorithm for outer materials and blister roof to investigate the effects on deformation and stress of an existing blister by changing the friction coefficient and elastic modulus of the material in contact with the blister.

Results

Through dynamics mode and harmonic frequency approach, we demonstrated that the loading frequency leads to dramatic changes of displacement and stress in spite of otherwise similar loading. Our simulations show that an increased friction coefficient does not necessarily result in an increase in either the stress on the hot spot or blister deformation; local maximum friction stress and Von-Mises stress exist for some friction coefficients over the wide range examined here. In addition, the stiffness of contact material on blistering is also investigated, and no significant effects on deformation and Von Mises stress are found, again at the range used. The model and method provided here may be useful for evaluating loading environments and contact materials in reducing blistering incidents.

Conclusion

The coupling finite element model can predict effects of friction coefficient and contacting materials stiffness on blister deformation and hot spot stress.

1. Introduction

Skin friction blisters, a frequent dermatology injury associated with intensive abrasion of skin against other surfaces, can inactivate an otherwise healthy individual, and be of significant consequence for such intensive events as athletics, military operations; for infantry soldiers carrying heavy equipment and supplies over long distances, blisters can account for 48% of the total injuries[1].

From a mechanical approach, abrasion will lead to “sore spots”, portion of the skin suffering excessive stress and strain, and finally results in blistering[2]. Actually, the blisters are caused from the frictional forces that mechanically separate the surface epidermal cells from the stratum spinosum[3]. Hydrostatic pressure then causes the area of separation to fill with a fluid similar in composition to plasma but with a lower protein level[4] (see Fig.1).

In the late 1950s and early 1970s [3, 5-8], friction blister became a focus on skin research and a special apparatus was designed for creating friction blisters. The instrument consists of a rubbing head to which various materials (including textiles) could be firmed attached. The head could be moved over the surface of any chosen skin site at a selected stroking rate under a given compressive load. The effect of skin moisture was also studied; a dry or near dry skin reduced the friction; intermediate degrees of moisture increased friction; and highly moist or completely wet skin decreased the friction again.

The rubbing head geometry, weight and attached material all affect the friction coefficient measurements[9]. Sivamani *et al*. [10, 11]utilized the UMT Series Micro-Tribometer, a tribology instrument that permits real-time monitoring and calculation of the important parameters in friction studies, to conduct tests on abdominal skin samples of four healthy volunteers. They then drew following conclusions that skin friction appears to be dependent on additional factors - such as age, anatomical site and skin hydration; the choice of the probe and the test apparatus also influence the measurement[10, 11] and the Amonton law does not provide an accurate description for skin surface[12].

Emollients and antiperspirants alleviated blistering. For instance, Darrigrand et al. and Reynolds et al. [13, 14] showed that antiperspirants reduced sweat rates and tended to decrease blisters, in spite of their side effect of introducing irritant dermatitis. Yet, antiperspirants with emollients abated irritant dermatitis but did not reduce total foot-sweat accumulation, blister or hot spot incidence, or blister severity, for the emollients may have altered the antiperspirant's chemical properties. In addition, the emollients may have acted as moisturizing agents, thus increasing the friction[15], and macerate the stratum corneum[16].

Clothing effects on blistering have also been documented. Herring and Richie [17] conducted a double-blind study to determine the effect of sock fiber composition on the frequency and size of blistering events in long-distance runners. Between two otherwise identical socks, except fiber contents, (i) 100% acrylic, (ii) 100% natural cotton, the acrylic fiber socks were associated with fewer blisters and smaller blister size compared to cotton socks.

An ulcer formation hypothesis [18] can also be applied to the blister forming from mechanical perspective. The plantar foot experiences a distributed shear and compressive stresses due to joint tangential and vertical forces. As a result, affected skin may slip (i) towards, (ii) away from or (iii) parallel to (i.e. a region that doesn't slip) each other. Coefficient of friction is defined as the ratio of the tangential/vertical forces, and blister is inhibited if the frictional coefficient is below a critical minimum ($\mu_{R\min}$).

Despite extensive friction blister studies, the prevalence or severity of friction blister remains difficult to predict and prevent. The reasons may lie in the variations of skin condition (surface roughness, hydration, adhesion between skin layers, etc.) among individuals as well as among different anatomic sites of the same person[19]. These variations may have pronounced effects on the dynamic contact of skin against outer-materials, and finally dictate the blister status.

This paper develops a blistering model by means of the finite element method. For given shear and normal forces, this model is able to account for the influences of friction coefficient, abrasion material stiffness, non-linear dynamic contact between skin and the material, and even the blistering geometry. The blister static and dynamic responses are obtained through mode frequency, and sweeping frequency harmonic analysis, and highly non-linear contact dynamics. The stresses on the hot spots are also compared to account for the effects of friction coefficients and material stiffness.

2. Model and Material properties

2.1 blister geometry model

The blister in the model consists of three parts (i) roofed skin, (ii) blister fluid, and (iii) basal cell layer. The roofed layer is composed of stratum granulosum, stratum corneum and a small segment of amorphous cellular debris[3]. The blister is considered as an ellipsoid shape with circular base, whose radius is viewed as the longer axis and set as 3 mm, and the height of the blister is the shorter axis. We simulated the dynamics of the blister model in ANSYS system (v.10.0, ANSYS Inc., Canonsburg, PA, USA, 2005).

The thickness of roofed skin is 55 μm with reference to the thickness of sole's stratum corneum[20]. The sole basal skin layer thickness is 1.6 mm from the surface measured by Ultrasound (20 MHz) [21]. The blister fluid is contained in the cavity by roofed skin and the basal skin layer. During the computation, the lateral surface (3-D) or sides (2-D) of basal skin layer are given displacement constrains.

2.2 Material properties

The Elastic modulus of roofed skin is about 13 MPa measured using *in vivo* dynamic (sonic) method [22], and the skin is assumed isotropic. For a steady or transient time span (a time much shorter than the skin relax time) simulation, a linear elastic constitutive behavior can be assumed. The Poisson ratio is taken as 0.4 [23]. The blister fluid is more or less like the plasma derived from blood with bulk modulus: 2150 MPa and apparent viscosity: 1.1x 10^{-9} MPa.s[5].

2.3 Contact algorithm

Materials contact skin with different friction coefficients and the effects on blister are highly significant [17, 24]. Such contact is an extremely non-linear dynamic problem. The augmented Lagrange algorithm is employed to cope with the challenges by using the Lagrange multipliers or penalty algorithm. So the total potential energy (virtual work) of the system can be expressed as [25, 26] ,

$$\delta\Psi = \int_{\Gamma}\left[\left(\lambda_N + \varepsilon_N g_N\right)\delta g_N + \left(\lambda_T + \varepsilon_T g_T\right)\delta g_T\right]dA \qquad (1)$$

where λ_N and λ_T are the Lagrange multipliers, ε_N and ε_T are the associated penalty parameters, and δg_N and δg_T are the virtual displacements. The subscripts N and T denote the normal and tangent directions, respectively. Equation 1 can be considered as a generalization of the Lagrange multiplier method where an additional term involving the contact tractions is added to the variational equation.

3. Result

The model thus designed is executed as a 3-D model with 0.5 ratio of radius. The mode natural frequencies calculated are shown in Table I, and the detailed descriptions on the mode and harmonic analysis is provided in Section 4. The lowest modal frequency is 28.38 Hz with a modal shape (resonance) shown in Fig. 2.

Fig. 3A and B showed the model harmonic analysis with sweeping frequency from 1 Hz to 7 Hz. The loads are 0.1 N and 0. 01 N respectively along the normal and the tangential directions on the tip of the blister. From the figures, the maximum displacement at 1.6 Hz is 0.031mm in Figure 3(A), less than 0.46 mm at 6 Hz in Figure 3(B).

To account for the effects on blistering of material properties in terms of the contacting friction coefficient and stiffness, we simplify the blister into a 2-D Finite element model with radius ratio 0.5 (Fig.4) for facile illustration.

In the 2-D model, line elements are used for the roofed skin and contacting material domain, the fluid elements are employed in the blister fluid domain, and the plane elements are in basal skin layer. To maintain displacement continuity, displacement constrained equations are applied to the interfaces between the roofed skin and blister blood, blister fluid and basal skin layer, respectively.

Two equal compressive forces are applied at the both ends of the contacting material at vertical direction. We assume the displacement at the two ends of the basal skin layer constrained. The contact algorithm is used to study the interactions between the contacting material and roofed skin. The contacting materials have an elastic modulus of 100 MPa and Poisson's ratio of 0.3. The two compressive forces are 0.1 N each and an1 mm horizontal displacement is added on the contacting material to generate the friction movement. The blister responses are obtained with frictional coefficient at 0 (frictionless), 0.1, 0.2, 0.3 and 0.4 respectively as shown in Fig.5.

The maximum tangential friction stress τ_m and normal pressure P_n happened on the top contact point of the blister shown in Table II.

With the same friction coefficient 0.1 and the same compressive loads, the elastic modulus of contacting materials changes to 80, 100, 120 MPa, the respective results of Von Mises stress in hot spot and displacement of blister show no significant changes so that only the case of 120MPa is provided in Fig.6.

4. Discussion

Frictional blisters, as a common problem in long distance running [27] and infantry road march[1], underlie the significance of understanding the dynamic response of body skin under intensive loading. Based on the numerical model, the eigenequation for the system can be established as

$$[K][\phi]-[\lambda][M][\phi]=[0] \quad (2)$$

Where $[K]$, $[M]$, $[\lambda]$,and $[0]$ are, respectively, the stiffness matrix, mass matrix, eigenvalue matrix, corresponding mode shape matrix, null matrix of the finite element assemblage [28].

We first computed the natural frequency of the skin system by finding the eigenfrequncy from Equation 2, as this frequency closely relates to the resonance, arisen due to the coincidence between the natural and the loading frequencies and leading to much greater deformation and stress, finally resulting in broken blisters.

We assume the gait frequency is from 1 Hz (normal walk) to 7 Hz (fast run). From the mode analysis result, the 1st order natural frequency is > 20 Hz (Table I). It means the loadings with human gait frequency can't excite resonance, and consequently unable to lead to the mode shape shown in Fig. 2.

Furthermore, to account for the frequency effects on blistering, a normal force 0.1 N and tangential force 0.01 N were loaded on the top point of the blister simultaneously. Then a sweeping frequency harmonic analysis as Equation 3 was conducted to investigate the blister deformation at different frequency values.

$$[K][\phi]-[\lambda][M][\phi]=[F] \quad (3)$$

where the forces are modulated by multiplying with a harmonic term $Sin(\omega t)$ with ω as the angular frequency and t the time, i.e., $F_i = ASin(\omega t)$ with A as the force amplitude.

The displacement amplitudes of blister at 1.6 Hz and 6 Hz are extracted and compared as shown Fig.3. The displacement amplitude at 6 Hz is 15-fold as great as that at 1.6 Hz. It suggests the displacement amplitude of blister is non-linearly proportional to the loading frequency before the resonance frequency. That is, even though the same forces are loaded on skin, the fast runner is more liable to blister formation than a normal walker. In spite of this seemingly simple fact, no existing experiments or theoretical analysis have demonstrated this.

Next, since blistering results from the friction interactions between skin and contact materials, the frictional coefficient contributes to a large degree to the process. Because of the blister symmetry about the related axis, a 2-D finite element model was employed here to examine the effects. We consider the deformation and the Von-Mises stress [29] at one hot point at interaction;

$$\sigma_e = \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{1/2}$$

or

$$\sigma_e = \left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\sigma_{xy}{}^2 + \sigma_{zy}{}^2 + \sigma_{xz}{}^2)\right]^{1/2} \quad (4)$$

where σ_i is the i^{th} principal stress, σ_j are stresses at $j = x, y, z$ axes, respectively, and $\sigma_{xy,zy,xz}$ are the corresponding shear stresses.

The effects of the frictional coefficient is calculated (Fig. 5), where four levels of the frictional coefficient from 0.0 to 0.4 are represented by the figures A to E, and at each level, e.g., A1 shows the blister displacement, and A2 represents the Von Mises stress. Results are summarized in Table II.

From the figures and table, it is clear that the influence of the frictional coefficient μ is not monotonic. In Table II, both stress τ_m and normal force P_n reach their corresponding maximum values at $\mu = 0.1$. Since the range of μ in our study, 0.0 to 0.4, covers a wide range, our conclusion seems valid in general, except perhaps the cases where the μ value becomes excessive.

The contact materials' stiffness also is a concern in blister forming and break. From our simulations, some interesting results are obtained. When the elastic modulus of contact material increased from 80 MPa to 100 MPa, then to 120 MPa under the same loads and friction coefficient, the tangential friction stress and normal pressure, displacement almost presented no change (as shown Fig.6). The result is somewhat different from the experiment[17] where different materials show different blistering scenarios. However, from our simulations, the elastic modulus shows no pronounced difference under calculated range. With complicated blistering forming process, in above experiments, the different blister events with contact materials may arise from the material moisture's difference.

5. Summary

Due to the experimental difficulties and skin variations, we designed a nonlinear dynamic finite element model to simulate the blister's deformation and stress under various loading conditions. From the mode and harmonic analysis, it is concluded that since our gait frequencies (both walking and running) are far below the lowest natural frequency of a blister, human activities are unlikely to lead to a resonance of blister, presumably with consequences such as broken blisters. Our analysis also indicates that increased frequency will lead to monotonically increasing deformation and stress of the blister. It is, however, not the case for the friction coefficient, that rising the friction coefficient does not necessarily cause greater stress or displacement of blister hot spot. In fact, there is a local maximum friction stress and Von-Mises stress at certain friction coefficient values. Furthermore, the change of elastic modulus in contact material (within 20-30% range) has not generated significant effects on both the deformation and Von Mises stress. The model and method provided here demonstrated their robustness in evaluating material properties to prevent blistering. As an on-going project, we will use different fabrics with variable periodic tension forces on skin to investigate the influences and also to further verify our model.

Acknowledgment

Authors appreciate the support from National Textile Center with grant NTC **S05-CD04.**

.

Reference:

1. Reynolds, K.L., White, J. S., Knapik, J. J., Witt, C. E., Amoroso, P. J., *Injuries and risk factors in a 100-mile (161-km) infantry road march.* Prev Med, 1999. **28**(2): p. 167-73.
2. Brueck, C., *The role of topical lubrication in the prevention of skin friction in physically challenged athletes.* Journal of Sports Chiropractic & Rehabilitation, 2000. **14**(2): p. 37-41.
3. Sulzberger, M.B., Cortese, T. A., Fishman, L., Wiley, H. S., *Studies on blisters produced by friction. I. Results of linear rubbing and twisting technics.* J Invest Dermatol, 1966. **47**(5): p. 456-65 contd.
4. Knapik, J.J.R., K. L.Duplantis, K. L.Jones, B. H., *Friction blisters. Pathophysiology, prevention and treatment.* Sports Med, 1995. **20**(3): p. 136-47.
5. Akers, W.A. and M.B. Sulzberger, *The friction blister.* Mil Med, 1972. **137**(1): p. 1-7.
6. Cortese, T.A., Jr., W.M. Sams, Jr., and M.B. Sulzberger, *Studies on blisters produced by friction. II. The blister fluid.* J Invest Dermatol, 1968. **50**(1): p. 47-53.
7. Sulzberger, M.B. and T.A. Cortese, *Observations on the blister base.* Br J Clin Pract, 1968. **22**(6): p. 249-50.
8. Naylor, P.F.D., *The skin surface and friciton.* Br. J. Dermatol., 1955. **67**: p. 239-248.
9. Gitis, N., Sivamani, R., *Tribometrology of skin.* Tribology Tansactions, 2004. **47**: p. 1-9.
10. Sivamani, R.K., Goodman, J., Gitis, N. V., Maibach, H. I., *Coefficient of friction: tribological studies in man - an overview.* Skin Res Technol, 2003. **9**(3): p. 227-34.
11. Sivamani, R.K., Wu, G. C., Gitis, N. V., Maibach, H. I., *Tribological testing of skin products: gender, age, and ethnicity on the volar forearm.* Skin Res Technol, 2003. **9**(4): p. 299-305.
12. Sivamani, R.K., Goodman, J.,Gitis, N. V.,Maibach, H. I., *Friction coefficient of skin in real-time.* Skin Res Technol, 2003. **9**(3): p. 235-9.
13. Darrigrand, A., Reynolds, K., Jackson, R., Hamlet, M., Roberts, D., *Efficacy of antiperspirants on feet.* Mil Med, 1992. **157**(5): p. 256-9.
14. Reynolds, K., Darrigrand, A.,Roberts, D., Knapik, J., Pollard, J., Duplantis, K., Jones, B., *Effects of an antiperspirant with emollients on foot-sweat accumulation and blister formation while walking in the heat.* J Am Acad Dermatol, 1995. **33**(4): p. 626-30.
15. Nacht, S.C., J.A.Yeung, D.Gans, E.H., *Skin Friction Coefficient - Changes Induced by Skin Hydration and Emollient Application and Correlation with Perceived Skin Feel.* Journal of The Society of Cosmetic Chemists, 1981. **32**(2): p. 55-65.
16. Akers, W.A., *Sulzberger on friction blistering.* Int J Dermatol, 1977. **16**(5): p. 369-72.
17. Herring, K.M. and D.H. Richie, Jr., *Friction blisters and sock fiber composition. A double-blind study.* J Am Podiatr Med Assoc, 1990. **80**(2): p. 63-71.
18. Davis, B.L., *Foot ulceration: hypotheses concerning shear and vertical forces acting on adjacent regions of skin.* Med Hypotheses, 1993. **40**(1): p. 44-7.

19. Zhong, W., Xing, M., Pan N. and Maibach H. I., *Textiles and human skin, Microcliamte,cutaneous reactions: overview*. Journal of toxicology: cutaneous and ocular toxicology, In Press.
20. Pierre Agache, P.H., editors; foreword by Howard I. Maibach, *Measuring the skin: non-invasive investigations, physiology, normal constants.* 2004: p. 748-749.
21. Black, M.M., *A modified radiographic method for measuring skin thickness.* Br J Dermatol, 1969. **81**(9): p. 661-6.
22. Takenouchi, M., H. Suzuki, and H. Tagami, *Hydration characteristics of pathologic stratum corneum--evaluation of bound water.* J Invest Dermatol, 1986. **87**(5): p. 574-6.
23. Pierre Agache, P.H., editors; foreword by Howard I. Maibach, *Measuring the skin: non-invasive investigations, physiology, normal constants.* 2004: p. 730-731.
24. Knapik, J.J., et al., *Influence of boot-sock systems on frequency and severity of foot blisters.* Mil Med, 1996. **161**(10): p. 594-8.
25. Wriggers, P., Zavarise, G., *Application of Augmented Lagrangian Techniques for Nonlinear Constitutive Laws In Contact Interfaces.* Communications in Numerical Methods In Engineering, 1993. **9**(10): p. 815-824.
26. Zavarise, G., Wriggers, P., Schrefler, B.A., *On Augmented Lagrangian Algorithms For Thermomechanical Contact Problems With Friction.* International Journal For Numerical Methods In Engineering, 1995. **38**(17): p. 2929-2949.
27. Mailler, E.A. and B.B. Adams, *The wear and tear of 26.2: dermatological injuries reported on marathon day.* Br J Sports Med, 2004. **38**(4): p. 498-501.
28. Bathe, K.-J., *Finite element procedures in engineering analysis.* 1982: p. 557-559.
29. Love, A.E.H., *A treatise on the mathematical theory of elasticity, 4th ed.* 1944.

Tables:

Table I The modal natural frequencies for model from 1st to 6th order to account for resonance frequency. The lowest frequency 28.38 Hz is far more than in sports competition.

Order	1st	2nd	3rd	4th	5th	6th
Frequency(Hz)	28.38	30.61	30.64	30.74	32.44	34.66

Table II The maximum tangential friction stress (τ_m) and normal pressure (P_n) at different friction coefficient. These two are critical to blister formation. In order to compare effect of the friction coefficient, τ_m and P_n are calculated.

μ	0	0.1	0.2	0.3	0.4
τ_m (MPa)	0	0.069	0.044	0.050	0.053
P_n (MPa)	0.175	1.548	0.852	0.843	0.840

Figure legends

Fig.1. Friction blister on skin. the shear and normal force separate the mid- or upper malpigian layer with roof composed of stratum corneum, stratum granulosum, and a small segment of amorphous cellular debris [3].

Fig.2. The 3-D blister with different radius ratio (A) 0.9 with finite element, (B) 0.2 in solid model

Fig.3. 1st order modal shape with frequency 28.38 Hz. When the loading frequency reaches this value, the blister shape will be excited.

Fig.4. the displacement of the blister at different frequencies of the excitation (A) 1.6 Hz and(B) 6 Hz. Blister displacement increased in response to rising moving frequency from 1.6 to 6 Hz.

Fig.5. A 2-D Finite element model of blister. The blue stands for the contacting materials, red for blister fluid, the purple for the basal skin layer, and the yellow for the potential contact element of roofed skin to contacting material. When fore or displacement is loaded on the contacting material, blister will be formed. Different friction coefficient and contact stiffness could be compared.

Fig. 6 The displacement and hot pot stress at 5 friction coefficient levels.
From A to E with subscript 1 shows blister displacement, Von Mises stress of the hot spot with subscript 2 and friction coefficient (A) 0, (B) 0.1, (C) 0.2, (D) 0.3 and (E) to 0.4. The effect of friction coefficient on blister displacement and stress can be compared.

Fig.7. (A) the displacement of blister and (B) the stress of hot spot. To account for stiffness effect of the contacting materials, the elastic modulus from 80 to 120 MPa of the worn outer the skin are compared for blister deformation and stress.

Fig.1

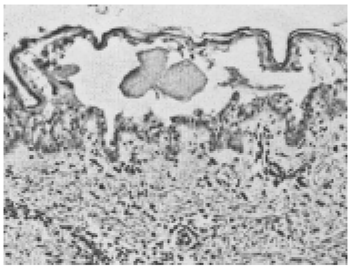
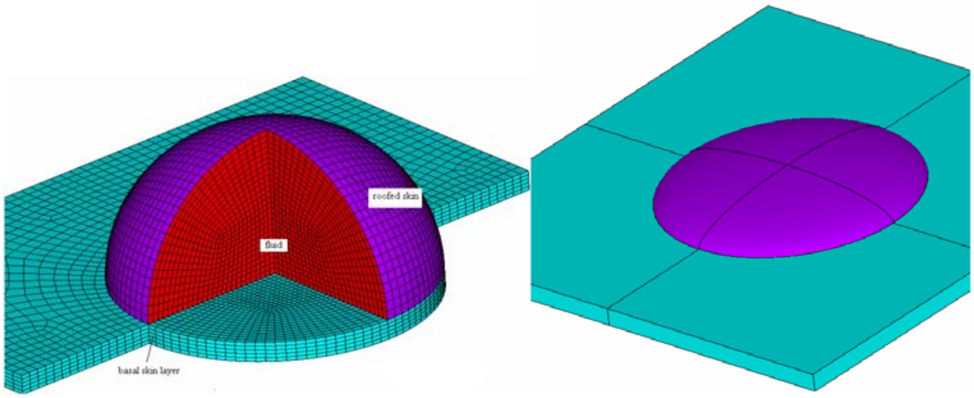


Fig.2



(A) (B)

Fig.3

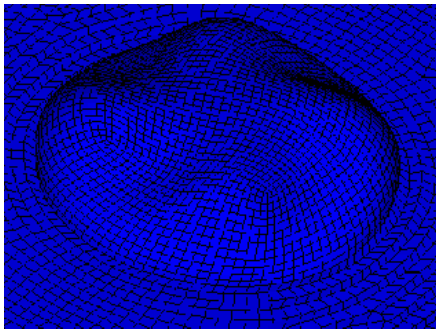
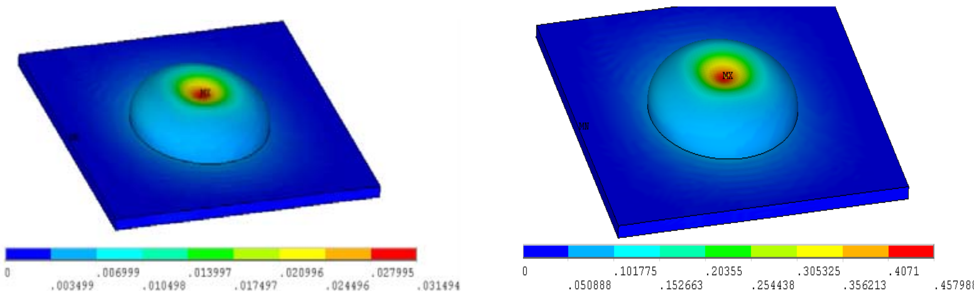


Fig.4


0
.006999
.013997
.020996
.027995
.003499
.010498
.017497
.024496
.031494
0
.101775
.20355
.305325
.4071
.050888
.152663
.254438
.356213
.457988

(A) (B)

Fig.5

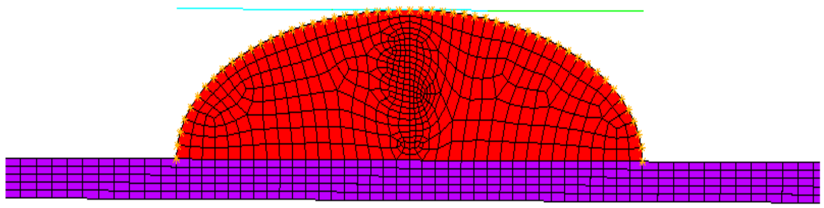


Fig. 6

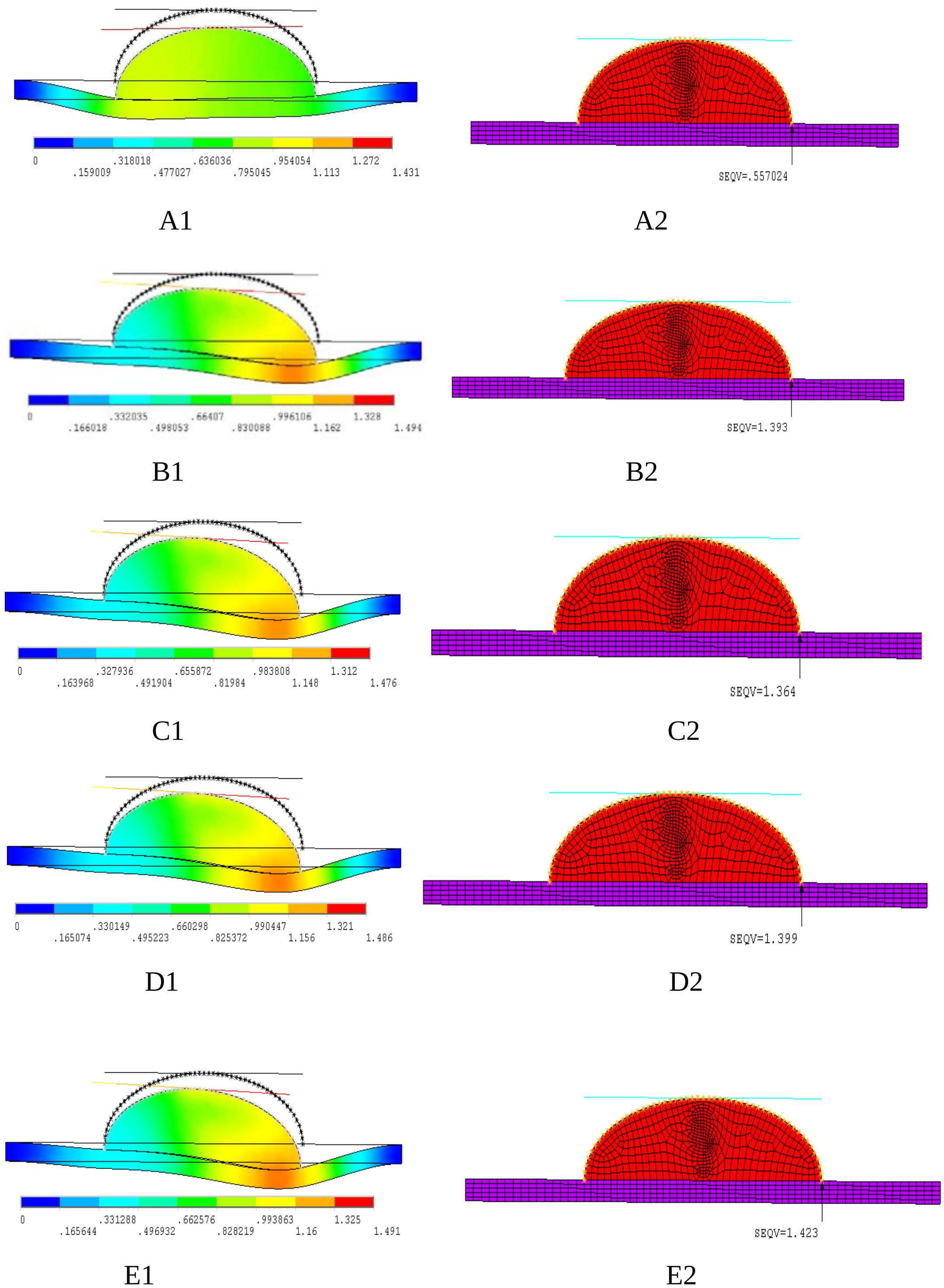
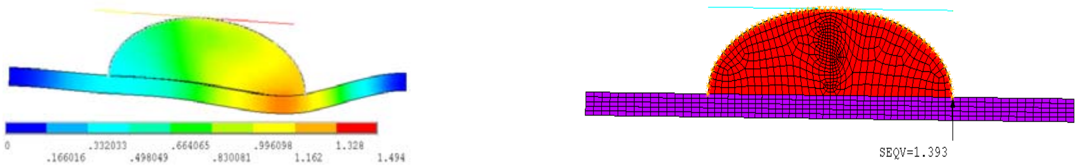

0 .159009 .318018 .477027 .636036 .795045 .954054 1.113 1.272 1.431
SEQV=.557024
A1
A2
0 .166018 .332035 .498053 .66407 .830088 .996106 1.162 1.328 1.494
SEQV=1.393
B1
B2
0 .163968 .327936 .491904 .655872 .81984 .983808 1.148 1.312 1.476
SEQV=1.364
C1
C2
0 .165074 .330149 .495223 .660298 .825372 .990447 1.156 1.321 1.486
SEQV=1.399
D1
D2
0 .165644 .331288 .496932 .662576 .828219 .993863 1.16 1.325 1.491
SEQV=1.423
E1
E2

Fig. 7


0
.166016
.332033
.498049
.664065
.830081
.996098
1.162
1.328
1.494
SEQV=1.393

A B