Anti-buckling design of cylindrical shells by local surface nanocrystallization

X S Xu¹, Z Zhao¹, C W Lim², W Wang¹, Z B Lian¹ and Z H Zhou¹, ³*

¹ State Key Laboratory of Structural Analysis for Industrial Equipment, Department of Engineering Mechanics, International Research Center for Computational Mechanics, Dalian University of Technology, Dalian, China;
² Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, China;
³ City University of Hong Kong Shenzhen Research Institute, Shenzhen, China.

*E-mail: zhouzh@dlut.edu.cn

Abstract. A novel surface modification method, namely the surface nanocrystallization technology, is introduced to enhance the anti-buckling performance of the metal cylindrical shells under axial impact loading. The effects of local nanocrystallization layouts are explored by evaluating the critical buckling loads of four local nanocrystallization layouts including the local circumferential stripes (LCS), local axial stripes (LAS), spaced latticed blocks (SLB) and oblique latticed blocks (OLB). Numerical results show that, compared to the untreated cylindrical shells, the critical buckling loads of the local nanocrystallized ones are significantly improved by the local nanocrystallization treatment. The critical buckling loads for the LAS design is improved by 80%. It is concluded that the local nanocrystallization treatment is a very promising method to design and manufacture the metal cylindrical shells with high anti-buckling performance.

1. Introduction
As a kind of fundamental thin-walled structure, the cylindrical shells are intensively applied in engineering areas such as aerospace industries, silo structures, architectural components, etc. While cylindrical shell tends to buckle when axial loading is applied on the structure, since the buckling deformation is a critical failure mode for cylindrical shells, the anti-buckling study and stability analysis have become significant problems and are widely investigated universally. In 1941, Karman [1] studied the post buckling behaviors both theoretically and experimentally, it is found that the cylindrical shell showed remarkably nonlinear properties under axial loading, which causing a dramatically decrease of anti-buckling resistance. Based on the perturbation method, Koiter [2] investigated the stability of cylindrical shells with initial imperfections and first proposed the imperfection sensitivity, which revealed that a minor imperfection will result in a sharp decrease for the structural bearing capacity. Since imperfections are unavoidable in practical engineering, it is advised to select the minimum post buckling load as the design criterion to evaluate the anti-buckling capacity. Yamaki [3] analyzed the elastic stability of cylindrical shells and gave a comprehensive treatise with accurate theoretical and experimental results, this work provided fundamental data for elastic stability study of cylindrical shells and has become a benchmark in buckling analysis. Due to
the extensively application of cylindrical shells in engineering, this kind of structures made by different materials and set with different boundary conditions or loadings are researched intensively.

For a structure under axial loading, three stages occurs subsequently when the axial load increases, the maximum compression load usually indicates the critical load of this specimen which also reflects its buckling resistance. To enhance the buckling resistance of cylindrical shells, various approaches have been explored in the past years. For cylindrical shells, the common approach is to adhere reinforced stringers to the structures, the influence of stringers’ sizes, intervals, arrangement angles and skin thicknesses are mainly investigated [4,5]. The cylindrical shells with stiffened stringers or ribs showed a great improvement on buckling resistance compared with the origin one, however, the additional structures will increase extra mass and meanwhile enhance the manufacturing difficulty. Besides, employing composite materials is another common measure to improve the buckling resistance. The carbon fiber reinforced plastic (CFRP) is utilized to enhance the structural strength. With the increasing numbers of layers, the cylindrical shells exhibited different degrees of anti-buckling resistance [6]. Even through the structures are strengthen by reinforced layers with specific arrangement, the delamination between layers still introduce defects in the shells and finally weakened the bearing capacity [7]. In consideration to the material cost, these methods need to be improved and modified for further application.

Since the current methods for enhancing buckling resistance still reflect limitations and weaknesses, there is a great demand for a technique to enhance the buckling resistance without any modification on structural sizes and configurations. In this research, an advanced surface modification method, that is the surface nanocrystallization technology is introduced in the anti-buckling design. The nanocrystallization technology is a method of strengthening, modification and fine processing to the solid surface through high impact frequency and velocity, this technology is well applied by Lu [8, 9] and can be realized through surface mechanical attrition treatment (SMAT), ultrasonic impact treatment (UIT) and other methods. After nanocrystallization, the mechanical properties of hardness, toughness and yield stress can be improved dramatically, and this technique has been applied on conventional metal materials like pure iron, low carbon steel, stainless steel, magnesium alloy, aluminum alloy and titanium alloy with dramatically mechanical improvements.

In this paper, the cylindrical shells with different local nanocrystallization layouts are investigated and the critical loads under axial loading are compared with the untreated models. The influence of local nanocrystallization distributions will provide a guidance for anti-buckling design of cylindrical shells. In addition, the nanocrystallization effect on cylindrical shells with various radius-thickness and radius-length ratios are also studied to explore the applicability of nanocrystallization for structures with diverse dimensions.

2. Local nanocrystallization distributions
The cylindrical shell with the diameter of 80mm, length of 160mm and thickness of 2mm is mainly studied in this paper, the material mechanical properties are set based on the stainless steel 304SS, the density, Young’s modulus and Possion’s ratio are set as 7960kg/m³, 196GPa and 0.27 respectively. According to the study on nanocrystallization [10], the engineering yield stress is enhanced from 287MPa to 878Mpa after surface nanocrystallization and the ultimate stress will reach to 929MPa. Based on the material properties, the simulation models are established via finite element software ABAQUS and the buckling deformation and critical loads are obtained.

Based on the geometric properties of cylindrical shells, various local nanocrystallization layouts, together with the untreated model, are designed and shown in figure 1. Four local nanocrystallization layouts, including the local circumferential stripes (LCS), local axial stripes (LAS), spaced latticed blocks (SLB) and oblique latticed blocks (OLB) are investigated first. The LCS model consists of four circumferential stripes with the same size, two stripes of them are nanocrystallized, while the other two stripes remain untreated. The nanocrystallized and untreated areas are stagger arranged, and the dark part and white part in figure 1(b) indicate the nanocrystallization and untreated areas respectively. Similarly, the model with four same-sized axial stripes including two of them nanocrystallized and the
other two untreated, is named as LAS and displayed in figure 1(c). As a combination of circumferential and axial distributions, the cylindrical shell can be divided into latticed blocks which contains 64 same-sized blocks. According to the arrangement of local nanocrystallization areas, two models named as SLB and OLB are designed for anti-buckling resistance, which are shown in figure 1(d) and (e). In all models, the dark parts demonstrate the nanocrystallized areas and the local nanocrystallization part keeps as the same degree of 50%, so that the critical loads of these four models can be compared and analyzed.

The models are established with shell elements and a rigid body is established to apply axial loading with the impact velocity of 10 m/s. The buckling displacement is set as 20mm, which is about 16.67% of the total length. The buckling modes and stress contours for the cylindrical shells are exhibited in figure 2.

![Figure 1. Local nanocrystallization design: (a) Untreated; (b) LCS; (c) LAS; (d) SLB; (e) OLB.](image)

From the buckling modes, it is found that with different local nanocrystallization layouts, the cylindrical shells show distinctive buckling modes. For the untreated model, there is a circumferential buckling deformation near the bottom of the structure. Since the structure is completely symmetric, the buckling deformation exhibit symmetric properties as well. The LCS model exhibits similar buckling deformation with the untreated one, which with a circumferential buckling fold. However, the top and bottom parts for this structure are nanocrystallized and strengthened while the middle part remained untreated. Thus, the buckling deformation is generated in the middle position of the model. In summary, the buckling position can be induced by local circumferential nanocrystallization layouts, the buckling deformation will first occur on the untreated part and then transit to otherwhere.

![Figure 2. Buckling modes of local nanocrystallization design: (a) Untreated; (b) LCS; (b) LAS; (c) SLB; (d) OLB.](image)
For the LAS, the buckling deformation occurs on the top of the structure. The nanocrystallized part undertakes more loads thus the deformation is a little different from the untreated parts. Compared with the untreated model and LCS, which display symmetric circumferential folds, the LCS shows an elliptical bending buckling fold instead of a circular one. Additionally, the models of SLB and OLB, which with latticed blocks nanocrystallization layouts show different buckling deformation with others. The SLB is designed with uniformly-spaced local nanocrystallization patterns and it is a symmetric local nanocrystallization design, thus the buckling deformation is similar to that of the untreated model. However, the nanocrystallized blocks exhibit higher strength for anti-buckling and the buckling deformation is different from the untreated blocks, where the buckling fold is polygonal for this situation. While for the OLB design, the nanocrystallization layout is oblique arranged, thus the structure exhibits a combination of compression and bending deformation. It is observed that the twisted deformation generates along the untreated parts, and the asymmetric buckling mode indicates instable anti-buckling properties.

The corresponding critical loads of the above five models are analyzed and listed in table 1, the enhancements of the local nanocrystallized structures are also calculated compared with the untreated model. From table 1, it is found that the LCS displays equivalent critical load as the untreated one. Due to the local nanocrystallization layout of LCS, the buckling deformation occurs on the untreated position. Even through this kind of local nanocrystallization design is capable of inducing buckling deformation on specific position, there is no help for the LCS design to enhance buckling resistance. However, the critical load of LAS design is significantly increased compared to the untreated model, where an 85.14% enhancement is observed for this condition. Since the nanocrystallization stripes are arranged with the same direction along the loading compression, this type of local nanocrystallization stripes can bear more impact and enhance the buckling resistance effectively. For the SLB, the critical load is increased by 25.58%, even though the buckling resistance is improved, the enhancement is much lower than the LAS model. Moreover, this kind of local nanocrystallization design is difficult to manufacture in practical engineering application. Lastly, regarding to the OLB, the critical load only increases in low degree and this local nanocrystallization design is not preferred for its local bending and instable asymmetric buckling modes.

Table 1. Critical loads of different local nanocrystallization layouts.

| Specimen | Untreated | LCS | LAS | SLB | OLB |
|----------|-----------|-----|-----|-----|-----|
| Critical load (kN) | 166.9 | 167.0 | 309.0 | 214.6 | 177.0 |
| Enhancement (%) | — | 0.06 | 85.14 | 28.58 | 6.05 |

3. Effect of axial stripe numbers
Based on the analysis results in previous section, it is demonstrated that the LAS design, which the local nanocrystallization stripes lay axially along the loading direction, exhibits the best anti-buckling properties under axial impact loading. To investigate the effect of axial stripe numbers on the structural critical loads, the cylindrical shells with different local nanocrystallization stripe numbers are further studied. Based on the LAS design, the cylindrical shells are circumferentially divided into 6, 8 and 10 same-sized stripes, which are named as LAS-6, LAS-8 and LAS-10 and their schematic diagrams are shown in figure 3. The nanocrystallized parts and untreated parts are alternating arranged so that the nanocrystallization areas keep as 50% for all models. It should be noticed that the LAS-4 in figure 3(a) is the same model with the LAS in previous section, and the LAS series with different stripes are analysed for anti-buckling properties.

The corresponding buckling modes are also displayed in figure 4 and the critical loads for cylindrical shells with different stripe numbers are shown in figure 5. From the buckling modes, it is observed that these models present similar buckling deformation which the circumferential folds come out on the top of the structures. Considering the gap between nanocrystallized areas and the untreated parts, the folds are not totally circular, and an obvious bending deformation can be observed for the
LAS-6. While with the increasing of stripe numbers, the structure tends to be uniformity and the buckling deformation is more symmetric and stable. From the stress contour plots, it is shown that when the stripe number increases, the stress concentrates to the top part of the structure and the bottom part remain undeformed.

**Figure 3.** LAS with varying axial stripe numbers: (a) LAS-4; (b) LAS-6; (c) LAS-8; (d) LAS-10.

**Figure 4.** Buckling modes of LAS series: (a) LAS-4; (b) LAS-6; (c) LAS-8; (d) LAS-10.

**Figure 5.** Buckling resistances of LAS model with varying stripe numbers.

Compared with the critical loads of the LAS series design with the untreated model, a dramatically anti-buckling enhancement can be found through figure 5. From the figure, it is discovered that for local nanocrystallized cylindrical shells with different axial stripe numbers, there is not a big
difference on critical loads. After local axial nanocrystallization, the critical loads increase to over 300kN, which indicate over 80% of enhancement compared with the untreated structure. Results reveal that the LAS layouts are effective for anti-buckling design, for superior buckling deformation with better symmetricity and stability, the axial local nanocrystallized shells with more stripes are preferred, while on the other hand, since the critical loads between them are on the same level, it is advised to select LAS-6 as the optimized design since it shows excellent buckling resistance both on critical load and buckling deformation, besides, the nanocrystallized areas are concentrated and this design is relatively easier for manufacturing.

4. Effect of geometric dimensions

The previous work mainly focuses on cylindrical shells with specific geometry sizes, in order to verify the effect of local nanocrystallization on anti-buckling design for cylindrical shells with different geometric dimensions, cylindrical shells with varying radius-thickness and length-radius ratios are studied in this section.

The cylindrical shells with the diameter of 80mm, length of 120mm and varying thicknesses of 0.5mm, 1.0mm, 2mm, 3mm are first studied, the shells with LAS-6 design and the corresponding untreated structures are analysed, the critical loads are exhibited in figure 6(a). With the rising of thickness, the critical loads also increase linearly for both the untreated model and the LAS-6 one. Figure shows that the local axial nanocrystallization is validated for cylindrical shells with different thicknesses, and the critical loads are enhanced by over 90%. Nevertheless, the surface nanocrystallization treatment is a manufacturing process and only applied on the surface layer of the material, thus the improvement of mechanical properties will decrease when the thickness is increasing. In practical manufacturing, the yield stress of thick shell is lower than that of the thin shell, and the discount on yield stress of thick shell after nanocrystallization will eventually reduce the anti-buckling effectiveness. Since the cylindrical shell of 0.5mm thickness presents inferior buckling resistance and ultra thin-walled shells are vulnerable by minor imperfections during the nanocrystallization process, thus it is concluded that the local nanocrystallization technique is best applied for cylindrical shells with the thicknesses between 1mm to 2mm.

The cylindrical shells with the diameter of 80mm, thickness of 120mm and varying lengths of 80mm, 120mm, 160mm, 200mm are investigated subsequently, their critical loads are displayed in figure 6(b). For the untreated models, the critical loads keep at the same level while there is a little decrease on critical loads for LAS-6 when the length increases. The reason for this difference is that after local axial nanocrystallization, the completely structural symmetricity is changed because of the material properties discrepancy between nanocrystallization parts and the untreated sections. The material difference in the structure will result in local buckling and subsequently lose its bearing
capacity. Despite of the slightly decrease for the critical loads of LAS-6 when its length increasing, this kind of design still provides an efficient anti-buckling enhancement. According to the analysis results, the enhancements of critical load reach to over 90% for lower length-radius ratios and 80% for higher ratios. From these results, it can be concluded that the local nanocrystallization is validated for cylindrical shells with varying geometric dimensions, and the critical loads are enhanced dramatically through LAS design.

5. Discussion
In this paper, the surface nanocrystallization technique is introduced in anti-buckling design and the cylindrical shells with different local nanocrystallization layouts and varying geometric dimensions are mainly investigated. Four local nanocrystallization layouts including the local circumferential stripes (LCS), local axial stripes (LAS), spaced latticed blocks (SLB) and oblique latticed blocks (OLB) are designed first to explore the influence of local nanocrystallization on critical loads enhancements. Results reveal that among the four layouts, the LAS exhibits excellent buckling resistance improvement compared with the untreated structure, where an over 80% enhancement on critical load is observed. The LAS design with various stripes are studied as well to evaluate the impact of stripe numbers on the anti-buckling resistance. Research results show that the stripes do not make a difference on the critical load while more local axial nanocrystallization stripes unify the material properties and generate more symmetric buckling modes. The LAS-6 model is selected for further investigation for size effect on cylindrical shells, and it is revealed that this kind of design maintain stable and valid for anti-buckling design of cylindrical shells with varying geometric sizes. Therefore, the local nanocrystallization treatment method is effective for enhancing critical loads of cylindrical shells under axial loading, and this study provides a new approach for anti-buckling design and can be well applied in practical engineering.

Acknowledgments
In this research work, the support of Shenzhen Science and Technology Funding Fundamental Research Program (No. JCYJ20170413141248626); Dalian Innovation Foundation of Science and Technology (No. 2018J11CY005) and High Level Talents Support Plan of Dalian of China (No. 2017RQ111) are gratefully acknowledged.

References
[1] Karman T 1941 The buckling of thin cylindrical shells under axial compression J. Aero. Sci. 8 303-12
[2] Koiter W 1945 On the stability of elastic equilibrium (Holland: Delft University of Technology)
[3] Yamaki N, Simitses G J 1984 Elastic stability of circular cylindrical shells (North-Holland)
[4] Krasovsky V and Kostyrko V 2007 Experimental studying of buckling of stringer cylindrical shells under axial compression Thin-Walled Struct. 45 877–82
[5] Sadeghifar M, Bagheri M, Jafari A A 2010 Multiobjective optimization of orthogonally stiffened cylindrical shells for minimum weight and maximum axial buckling load Thin-Walled Struct. 48 979-988
[6] Draidi Z, Bui T, Limam A, Tran H and Bennani A 2018 Buckling behavior of metallic cylindrical shell structures strengthened with CFRP composite Adv. Civ. Eng. 2018
[7] Tafreshi A 2004 Efficient modelling of delamination buckling in composite cylindrical shells under axial compression Compos. Struct. 64 511–20
[8] Lu K and Lu J 1999 Surface nanocrystallization (SNC) of metallic materials-presentation of the concept behind a new approach J. Mater. Sci. Technol. 15 193
[9] Lu K and Lu J 2004 Nanostructured surface layer on metallic materials induced by surface mechanical attrition treatment Mater. Sci. Eng. A 375 38–45
[10] Chen A, Li Y, Zhang J, Pan D and Lu J 2013 The influence of interface structure on nanocrystalline deformation of a layered and nanostructured steel Mater. Des. 47 316–322