Prediction and validation of buckling stress ($\sigma_{\text{cr}}$) of the ceramic honeycomb cell walls under quasi-static compression

Pandu Ramavath¹, Papiya Biswas¹, Nakula Ravi¹ and Roy Johnson¹*

Abstract: Alumina- and cordierite-based honeycombs with varying relative densities were extruded and sintered at the respective sintering temperatures. Solid samples are also prepared under identical conditions and flexural strength ($\sigma_f$) was estimated by three-point bend measurements. Buckling stress of honeycombs are predicted based on $\sigma_f$ using standard equations and validated with quasi-static compression test along the channels of honeycombs with varying relative densities. The discrepancy observed on calculated and measured values is correlated with the pre-existing flaws indicating the criticality in close control of processing parameters.

Subjects: Ceramics & Glass; Material Fracture Mechanics; Materials Processing

Keywords: bulking load; compression; fractography; honeycomb

1. Introduction

Cellular ceramics such as honeycomb structures and reticulated foams are composed of a solid phase and a void phase. Ceramic honeycombs possess an array of prismatic cells and foams have polyhedral cells. Unlike solids, as they are composites, they exhibit unique combination of properties and are a function of their (i) relative density, (ii) material of construction, and (iii) geometry of cells (Alvin, Lippert, & Lane, 1991; Mahajan & Johnson, 2002; Then & Day, 2000). Gibson and Ashby (1997) have demonstrated that failure in ceramic honeycomb predominantly takes place due to tension

© 2016 The Author(s). This open access article is distributed under a Creative Commons Attribution (CC-BY) 4.0 license.
depending on the net section stress in the plane normal exceeds tensile strength of the material of its construction (Banhart & Baumeister, 1998; Miltz & Gruenbaum, 1981; Shaw & Sata, 1966; Thornton & Magee, 1975). Ceramic honeycomb structures with tailored configurations designed to exhibit thermomechanical properties currently catering to diverse applications. Some of the potential applications of ceramic honeycombs ranges from high surface area supports for heterogeneous catalysis, especially for environmental control, biotechnology and biomedical applications, molten metal filtration, gas particulate filtration, acoustic transfer in ceramic burners, energy conservation and heat transfer, solar radiation conversion, fuel cell, and aerospace. (Agrafiotis et al., 2007; Howell, Hall, & Ellzey, 1996; Kummer, 1980; Machida, Yamada, Hijikata, & Ichikawa, 1999; Wetzko, Belzner, Rohr, & Harbach, 1999; Yamaguchi, Shimizu, Suzuki, Fujishiro, & Awano, 2009). It is evident that ceramic honeycombs are widely explored for many applications, they are not employed for energy absorption applications though earlier studies reported their potential through mechanisms of failure (Johnson et al., 2003; Saha, Kumari, Johnson, & Eswara Prasad, 2010; Vipin, Johnson, Saha, Ganesh, & Mahajan, 2003; Yamada et al., 2000).

In the present study, two ceramic materials, namely cordierite and alumina has been extruded in to honeycombs of varying wall thickness and unit cell length and sintered. The samples were further subjected to compressive deformation in the direction parallel to the channels. Additionally, solid samples were also fabricated under identical conditions and were subjected to bend test. An attempt has also been made to correlate predicted buckling stress and experimentally obtained values based on the microstructural observations.

2. Experimental procedure
Honeycombs with different configurations are fabricated using the extrusion technique of Bagley et al. using an indigenously fabricated die (Bagley, 1974). In order to prepare the cordierite honeycombs (designated as CHC1, CHC2, and CHC3) the precursor oxides of clay, talc, and alumina were mixed according to the stoichiometry. Alumina honeycombs (designated as AHC1, AHC2, and AHC3) were prepared using α-alumina, procured from commercial sources (MR-01 grade. Hindalco, India). The formulations was mixed in a ball mill with 2–3% by weight of methylcellulose as binder and 1% of polyethylene glycol by weight as plasticizer and 30–37% of water by weight depending on the formulations for 20 minutes to obtain homogeneous dough. The samples are extruded into honeycombs with varying relative densities. Solid samples were also prepared using the formulations under identical conditions. The samples are subjected to microwave drying followed by sintering at 1,420°C/2 h and 1,650°C/2 h for cordierite and alumina samples in a laboratory furnace, respectively. The samples are characterized for their density using the Archimedes principle (ASTM C-792). Solid samples were machined to the rectangular specimens of 45 × 4 × 3 mm³ sizes and then ground and polished for the evaluation of flexural strength using ASTM C-1161-02C (ASTM Standard 1161-02C 2008e1, 2008). Honeycombs were cut into 20 × 20 × 20 mm³ and subjected to quasi-static compression using a universal testing machine (Instron 4483, UK) parallel to the channels and compressive strength was calculated based on load/area.

3. Results and discussion
Densities of the cordierite and alumina samples were found to be 2.1 and 3.75 g/cm³, respectively. Relative density of the honeycombs were estimated based on \((t^2 + 2tl)/(t + l)^2\), where \(l\) is the unit cell length and \(t\) is the wall thickness as represented in Figure 1 and the extruded honeycombs are shown in Figure 2. Sample ID, unit cell parameters, and the relative density of the samples are shown in Table 1.

Stress–strain curve obtained from three point bend test of the solid cordierite and alumina samples (relative density of 1.0) are shown in Figure 3(a) and (b), respectively. Though three samples are evaluated in each case only representative curves are presented and flexure strength are taken as the average of three readings. In case of cordierite and alumina sample flexure strength test following ASTM C-1161-02C measurement have shown \(\sigma_f\) 50 and 250 MPa, respectively. According to
The ratio of failure stress under tension of honeycomb to failure stress of the cell wall material can be calculated based on Equation (1). Compressive strength of honeycombs is approximately 12 times than that of its tensile strength. Hence, in case of honeycomb samples under compression the buckling stress can be defined by Equation (2).

\[
\frac{\sigma_{th}}{\sigma_{ts}} = \frac{(l + t) + lt}{(l + t) + (l + t)} = \frac{(2l + t)t}{(l + t)^2}
\]  \tag{1}

\[
\frac{\sigma_{crit}}{\sigma_{ts}} = \frac{12(2l + t)t}{(l + t)^2}
\]  \tag{2}

It is known that the tensile strength of ceramic material is approximately 0.6 times of its flexural strength. Following Equation (2), \(\sigma_{ts}\) is calculated for the cordierite and alumina honeycomb samples,
and the buckling stress at which the cells collapses ($\sigma_{crt}$) is shown in Table 2. Further, Table 2 shows the calculated and measured compression strength values of the honeycomb samples.

A typical stress–strain curve obtained from quasi-static compression tests of representative alumina (AHC1) and cordierite (CHC1) honeycombs are shown in Figure 4(a) and (b) respectively. Successive stages of failure of honeycomb samples under compressive stresses are shown in Figure 5 for alumina and Figure 6 for cordierite, respectively. It is evident from Figure 4 that that stress–strain curve of the alumina and cordierite honeycombs are distinctly different. Alumina honeycombs exhibited almost a linear behavior reaching a peak value of 130 MPa with an abrupt drop at a compressive strain of 2.8%. In the case of cordierite honeycombs, the initial linear response was followed by the first drop at the strain of 0.99% indicating the failure of the rib with the critical flaw. This is followed by increase in the compressive stress to the maximum of 3.77 MPa with close to a plateau like behavior with many kinks which extending up to a percentage strain of 2.15 beyond which failure occurs with visibly collapse of the structure. Unlike cordierite honeycombs alumina honeycombs has followed a steep fall in flow stresses indicating catastrophe as is also evident from the successive stages of failure shown in Figure 5. There is a discrepancy between $\sigma_{crt}$ calculated and measured which is found to be dependent on the relative density. (Brenzy, Green, & Dam, 1989; Kainer & Reh, 1991) The maximum variation of 87% is observed with the relative density of 0.3 which is relatively same ranging from 76 to 70 for alumina honeycombs with relative density of 0.64–0.51. In the case of cordierite, failure occurred through buckling of cell walls rather though the brittle fracture is evident. Figure 6 clearly shows that the cracks initiated are restricted and grown vertically rather than spreading in to the neighboring column showing load bearing capability. In case of cordierite honeycombs also a similar trend is observed with $\sigma_{crt}$ calculated and measured as in the case of alumina honeycombs.
Extrusion processing of honeycombs is very complex, as rheological property of the dough plays a critical role in lateral flow of the dough followed by the knitting with adjacent cross-section within the die while shaping of the honeycomb. Further, the rheological properties are dictated by various factors such as particle size and morphology of the powder in addition to binder and plasticizer used. Further the extent of solid loading and high shear mixing to achieve homogeneous dough is also very critical to obtain defect free extrusions. The larger discrepancy between $\sigma_{\text{cr}}$ values calculated and measured in case of honeycombs investigated, especially for cordierite honeycombs can be attributed to the presence of pre-existing flaws indicating the requirement of more stringent control of processing parameters. Additionally, wall thickness of honeycombs close to 1 mm processed in the present study will be effective in shear along the die wall and internal shear may not be effective in the bulk leaving agglomerates. This can be further improved by providing longer die land in order to ensure homogeneous shear as the retention and hence shearing of agglomerates are allowed to take place.

### Table 2. Calculated and measured compression strength values of the honeycomb samples

| Sample ID | $\sigma_{ts}$ (MPa) calculated | $\sigma_{\text{cr}}$ (MPa) calculated | $\sigma_{\text{cr}}$ (MPa) measured | % variation of calculated and measured values |
|-----------|-------------------------------|--------------------------------------|-----------------------------------|---------------------------------------------|
| CHC1      | 18                            | 121.01                               | 31.5                              | 74                                          |
| CHC2      | 18                            | 97.53                                | 7.9                               | 92                                          |
| CHC3      | 18                            | 64.14                                | 3.7                               | 94                                          |
| AHC1      | 135.6                         | 963.21                               | 230                               | 76                                          |
| AHC2      | 135.6                         | 797.98                               | 166                               | 79                                          |
| AHC3      | 135.6                         | 471.79                               | 63                                | 87                                          |

Note: $\sigma_{\text{cr}}$: compression strength is an average of five readings.
while extrusion processing minimizing the defect formation. One of the other probable reasons for larger discrepancy between $\sigma_{crt}$ values calculated and measured can be attributed to the limitation of Equation (2) in predicting the buckling stress in case of honeycombs with wall thickness close to 1 mm.

4. Conclusions
Honeycomb structures based on alumina and cordierite ceramics along with their solid counter parts are processed. Based on the flexural strength ($\sigma_f$) of solid samples buckling stress of honeycombs under compression were predicted using standard equations. Significant variations are observed between predicted and experimental values in both formulations. Stress–strain curve of the alumina and cordierite honeycombs are found to be distinctly different. The larger discrepancy between $\sigma_{crt}$ values calculated and measured could be attributed to the pre-existing flaws indicating the requirement of close control of process parameters with respect to dough and extrusion die. One of the other probable reasons the discrepancy could be the limitation of Equation (2) in predicting the buckling stress in case of honeycombs with wall thickness close to 1 mm.

Funding
The authors received no direct funding for this research.

Author details
Pandu Ramavath1
E-mail: pandu@arci.res.in
Papiya Biswas1
E-mail: papiya@arci.res.in
Nakula Ravi1
E-mail: ravi@arci.res.in
Roy Johnson1
E-mail: rojjohnson@arci.res.in
1 Centre for Ceramic Processing, International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), Hyderabad 500005, India.

Citation information
Cite this article as: Prediction and validation of buckling stress ($\sigma_{crt}$) of the ceramic honeycomb cell walls under quasi-static compression, Pandu Ramavath, Papiya Biswas, Nakula Ravi & Roy Johnson, Cogent Engineering (2016), 3: 1168068.

References
Agrafiotis, C. C., Mavroidis, I., Konstandopoulos, A. G., Hoffschmidt, B., Stobbe, P., Romero, M., & Fernandez-Quero, V. (2007). Evaluation of porous silicon carbide monolithic honeycombs as volumetric receivers/collectors of concentrated solar radiation. Solar Energy Materials & Solar Cells, 91, 474–488.

Alvin, M. A., Lippert, T. E., & Lane, J. E. (1991). Assessment of porous ceramic materials for hot gas filtration application. American Ceramic Society Bulletin, 70, 1491–1498.

Ashby, M. F., Evans, A. G., & Hutchinson, J. W. (1998). Cellular design guide. Cambridge: Cambridge University Press.

ASTM Standard 1161-02C 2008e1. (2008). Test method for flexural strength of advanced ceramic at ambient temperatures, annual book of ASTM standards (Vol. 15.01, PA2008). West Conshohocken: American Society for Testing and Materials.

Brenzy, R. D. (1974). Extrusion method for forming thin-walled honeycomb structures. US Patent No. 3, 790, 654.

Banhart, J., & Baumeister, J. (1998). Deformation characteristics of metallic foams. Journal of Materials Science, 33, 1431–1440.

Gibson, L. J., & Ashby, M. F. (1997). Cellular solids (2nd ed.). Cambridge: Cambridge University Press.

Howell, J. R., Hall, M. J., & Elzey, J. L. (1996). Combustion of hydrocarbon fuels within porous inert media. Progress in Energy and Combustion Science, 22, 121–145.

Johnson, R., Vipin, J., Karnat, S. V., Ganesh, I., Soha, B. P., & Mahajan, Y. R. (2003). Studies on energy absorption characteristics of cordierite–mullite honeycombs. Journal of Advanced Materials, 35, 3–8.

Kainer, H., & Reh, H. (1993). High performance ceramics III.
The product catalysts (PartII). Interceram, 40, 99–108.
Kummer, J. T. (1980). Catalysts for automobile emission control. Progress in Energy and Combustion Science, 6, 177–199.
http://dx.doi.org/10.1016/0360-1285(80)90006-4
Machida, M., Yamada, T., Hijikata, T., & Ichikawa, Y. (1999). Ceramic honeycomb catalytic converter. US 5866079.
Mahajan, Y. R., & Johnson, R. (2002). Cellular solid: Unique engineering solid. In R. Chidambaram (Ed.), Materials research: Current scenario and future projections. Bangalore: Materials Research Society of India.
Miltz, J., & Gruenbaum, G. (1981). Evaluation of cushioning properties of plastic foams from compressive measurements. Polymer Engineering and Science, 21, 1010–1014.
http://dx.doi.org/10.1002/0032-5998(1981)15:48-263
Saha, B. P., Kumari, S., Johnson, R., & Esware Prasad, N. (2010). Effect of relative density on the compressive flow behaviour of cordierite and cordierite: Mullite honeycombs. Transactions of the Indian Institute of Metals, 63, 701–706.
http://dx.doi.org/10.1007/s12666-010-0108-8
Shaw, M. C., & Sato, T. (1966). The plastic behavior of cellular materials. International Journal of Mechanical Sciences, 8, 489.
http://dx.doi.org/10.1016/0020-7403(66)90019-1
Then, P. M., & Day, J. P. (2000). Most effective use of the catalytic converter substrate. Interceram, 49, 20-23.
Thornton, P. H., & Magee, C. L. (1975). Deformation characteristics of zinc foam. Metallurgical Transactions A, 6, 1801–1807.
http://dx.doi.org/10.1007/BF02642310
Vipin, J., Johnson, R., Saha, B. P., Ganesh, I., & Mahajan, Y. R. (2003). Effect of rubber encapsulation on the comparative mechanical behavior of ceramic honeycomb and foam. Materials Science and Engineering A, 347, 109–122.
Wetzko, M., Belzner, A., Rohr, F. J., & Harbach, F. (1999). Solid oxide fuel cell stacks using extruded honeycomb type elements. Journal of Power Sources, 83, 148–155.
http://dx.doi.org/10.1016/S0378-7753(99)00289-X
Yamada, Y., Shimojima, K., Mabuchi, M., Nakamura, M., Asahina, T., Mukai, T., ... Higashi, K. (2000). Compressive deformation behavior of Al₂O₃ foam. Materials Science and Engineering A, 277, 213–217.
http://dx.doi.org/10.1016/S0921-5093(99)00541-9
Yamaguchi, T., Shimizu, S., Suzuki, T., Fujishiro, Y., & Awano, M. (2009). Evaluation of extruded cathode honeycomb monolith-supported SOFC under rapid start-up operation. Electrochimica Acta, 54, 1478–1482.
http://dx.doi.org/10.1016/j.electacta.2008.09.029