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MATERIALS ENGINEERING | RESEARCH ARTICLE

Prediction and validation of buckling stress (σ_{crt}) of the ceramic honeycomb cell walls under quasi-static compression

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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 (σ_f) was estimated by three-point bend measurements. Buckling stress of honeycombs are predicted based on σ_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 posses 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

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PUBLIC INTEREST STATEMENT

Man-made honeycomb structures with engineered inter-connected network of plates mimicking the naturally occurring honeycombs have received a renewed attention recent past. This is because of the flexibility in tailoring the variables such as relative density, cell wall material, and geometry, in order to derive a combination of light weight with thermal, acoustic and mechanical properties to cater a wide range of applications. Ceramic honeycombs are regarded as one of the significant product in the ceramic world owing to the wide range of applications in the area of energy and environment. Some of the examples are in the field of automobile pollution control, molten metal filtration, energy efficient air heating, fuel cells solar radiation conversion, etc. However, ceramic honeycombs being inherently brittle they have not been fully explored for energy absorption properties and hence the current work is envisaged to investigate the mechanical deformation behavior of ceramic honeycombs.

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 $45 \times 4 \times 3$ mm^3 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 $20 \times 20 \times 20$ mm^3 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/cm^3, 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 σ_{fs} 50 and 250 MPa, respectively. According to

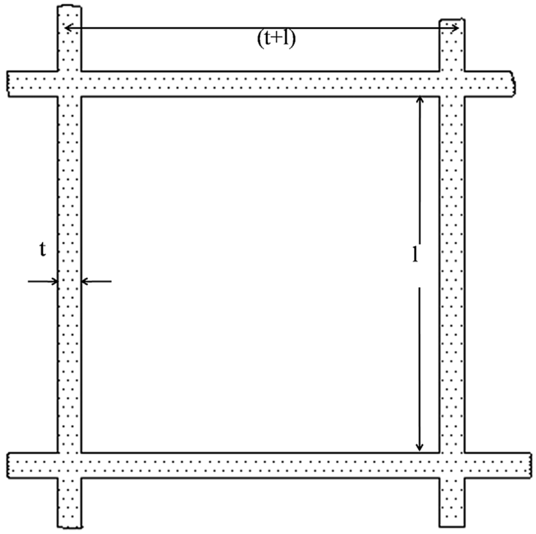


Figure 1. Unit cell showing wall thickness and unit cell length (Schematic).

(Ashby, Evans, & Hutchinson, 1998), the ratio of failure stress (σ_{th}) under tension of honeycomb to failure stress of the cell wall material (σ_{ts}) 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).

$$\frac{\sigma_{th}}{\sigma_{ts}} = \frac{(l+t)+lt}{(l+t)+(l+t)} = \frac{(2l+t)t}{(l+t)^2} \quad (1)$$

$$\frac{\sigma_{crt}}{\sigma_{ts}} = \frac{12(2l+t)t}{(l+t)^2} \quad (2)$$

It is known that the tensile strength of ceramic material is approximately 0.6 times of its flexural strength. Following Equation (2), σ_{ts} is calculated for the cordierite and alumina honeycomb samples,

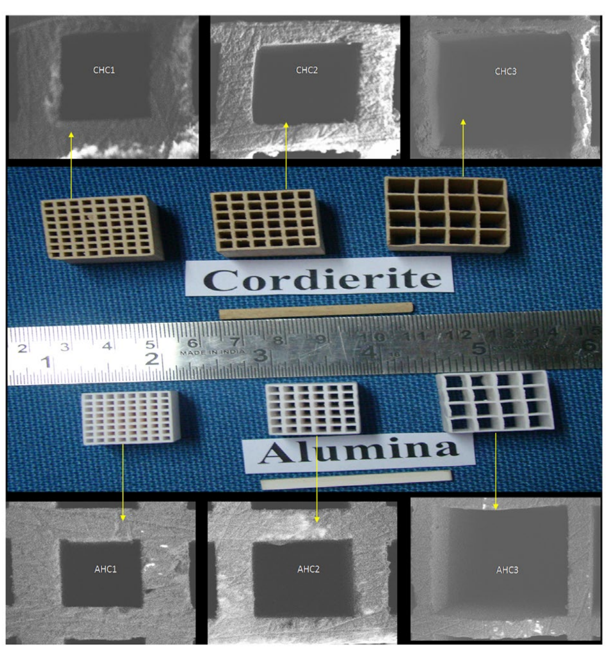


Figure 2. Extruded and sintered honeycombs with unit cell images.

Table 1. Unit cell parameters and relative density of the honeycombs

Sample ID	Wall thickness (*t*) (mm)	Unit cell length (*l*) (mm)	Relative density $(t^2 + 2tl)/(t + l)^2$
CHC1	1.28	2.52	0.5602
CHC2	1.31	3.74	0.4515
CHC3	1.41	7.32	0.2969
AHC1	0.933	1.65	0.5919
AHC2	0.962	2.4	0.4904
AHC3	0.943	5.05	0.2899

and the buckling stress at which the cells collapses (σ_{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 σ_{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 σ_{crt} calculated and measured as in the case of alumina honeycombs.

Figure 3. Stress–strain curve obtained from 3 point bend test of the solid (a) alumina and (b) cordierite.

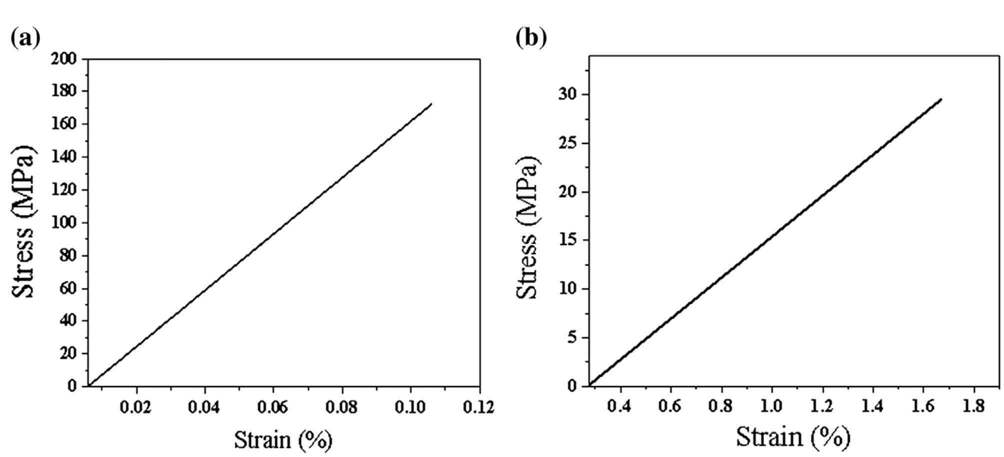


Table 2. Calculated and measured compression strength values of the honeycomb samples

Sample ID	σ_{ts} (MPa) calculated	σ_{crt} (MPa) calculated	σ_{crt} (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: σ_{crt}: compression strength is an average of five readings.

Figure 4. Stress–strain curve obtained from compression tests of representative honeycombs (a) alumina (AHC1) and (b) cordierite (CHC1).

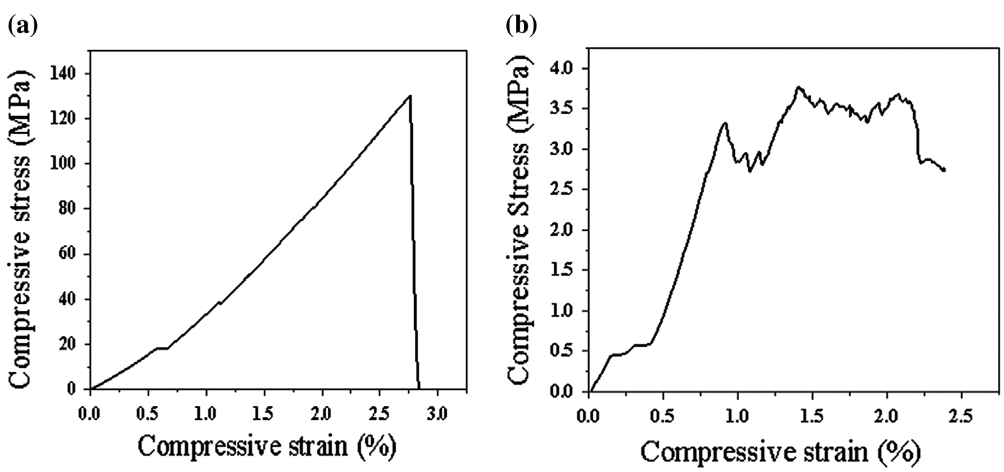
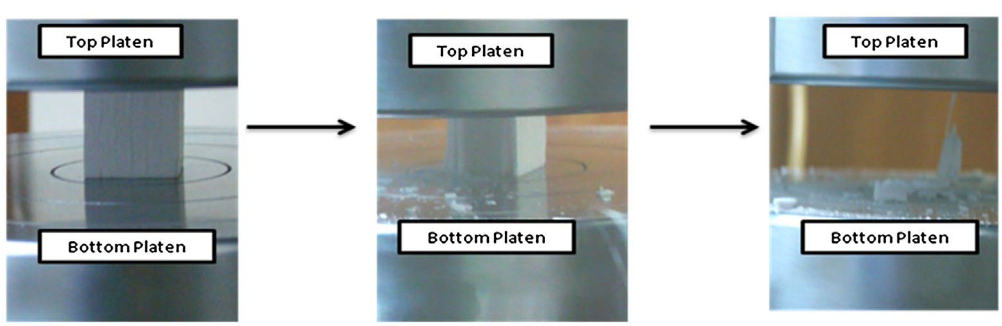
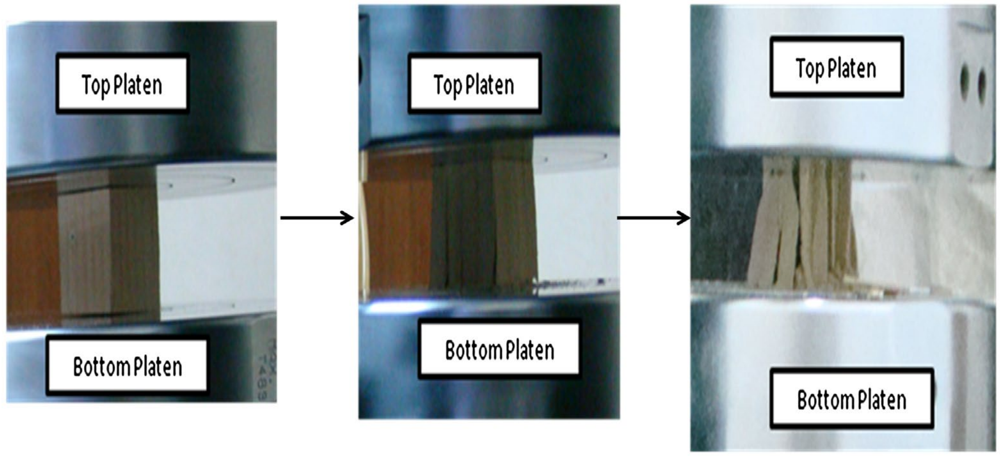


Figure 5. Progressive failure of alumina honeycomb samples under quasi-static compression.



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 σ_{crt} 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

Figure 6. Progressive failure of cordierite honeycomb samples under quasi-static compression.



while extrusion processing minimizing the defect formation. One of the other probable reasons for larger discrepancy between σ_{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 (σ_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 σ_{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.

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