Feasibility study of structural systems made from ceramics

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Abstract - The objective of this paper is to investigate the feasibility of making structural systems from ceramics. Segmental and composite systems are quantitatively studied, partial application of ceramics to traditional systems is considered, and the special application of a lunar base is studied. The quantitative and qualitative studies made indicate both advantages and disadvantages for ceramics in structural systems. However, the structural systems proposed may stimulate further studies to eliminate the disadvantages.

In a previous paper the authors' made a qualitative analysis of the applicability of advanced ceramics to construction based on a set of criteria; the results indicated both advantages and disadvantages in their use. To understand clearly and quantitatively the performance of advanced ceramics for construction, it was suggested that structural systems in which the unique properties of advanced ceramics could be optimally utilized should be developed.

In this paper feasible structural systems for ceramics are investigated and the future utilization and mechanical performance of ceramics in construction are considered.

Candidate materials
The mechanical properties of typical ceramics are given in Table 1. Examples 1 and 2 represent high-performance ceramics: lithium aluminosilicate and silicon carbide, respectively. This table shows the considerable advantages of certain properties of ceramics over those of concrete and steel, indicating the potential of structural systems made from ceramics. However, the mechanical properties of monolithic ceramics are not adequate for use in structural systems because monolithics are brittle materials that usually fail abruptly without giving much warning in advance. Moreover, owing to their brittleness, the strength of ceramics is very sensitive to the flaw size in the material. Ceramic parts made from the same material may thus have very different strengths, making ceramics materials of low reliability. So ceramic toughness must be improved for structural systems.

There are several ways of improving ceramic toughness, but fibre reinforcement is by far the most effective means. It has been shown that continuous-fibre reinforcements can greatly improve the reliability of ceramics because the sensitivity of first-cracking strength to flaw size is significantly reduced (first-cracking strength is the applied tensile stress at which an inherent flaw will propagate unstably across the whole section of the material). After first-cracking, the bridging of the crack by fibres allows the material to take further load. With increased loading, multiple cracks form, producing a pseudo-strain-hardening effect similar to that in metals. This quasi-ductility provides a warning before final failure and also allows for stress redistribution to less severely loaded parts.

While continuous-fibre-reinforced ceramics have been shown to possess the desirable properties described, their use has been limited to parts of relatively simple geometric shape because it is very difficult and costly to construct continuous-fibre-reinforcing mesh for complex shapes. However, short fibres can be mixed with ceramic powders and formed into any shape by traditional powder compaction techniques.

Table 1 Mechanical properties

<table>
<thead>
<tr>
<th></th>
<th>Example 1</th>
<th>Example 2</th>
<th>Concrete</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$ (Mg m$^{-3}$)</td>
<td>2.2</td>
<td>2.3</td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td>Compressive strength, $f_c$ (MPa)</td>
<td>1300</td>
<td>2000</td>
<td>40</td>
<td>220</td>
</tr>
<tr>
<td>Young's modulus $E$ (GPa)</td>
<td>83</td>
<td>400</td>
<td>30</td>
<td>210</td>
</tr>
<tr>
<td>$f_c / \rho$</td>
<td>590</td>
<td>910</td>
<td>17</td>
<td>28</td>
</tr>
<tr>
<td>$E / \rho$</td>
<td>38</td>
<td>180</td>
<td>13</td>
<td>27</td>
</tr>
</tbody>
</table>

Table 1: Mechanical properties

Example 1 is typical of lithium aluminosilicate, glass-ceramics
Example 2 is typical of silicon carbide, high-performance ceramics
HEAT UP MOULD

PUT ON CERAMIC POWDER AND SHORT FIBER IN THIN LAYERS

MELT ONE LAYER OF MATERIAL AFTER THE OTHER

COMPOSITE 1

COMPOSITE 2

CERAMICS SHORT FIBER

CERAMICS SHORT FIBER

Fig 2 Casting technique

Steel or FRP Tendon

Ceramics

Elevation

Section

Fig 3 Segmental beam

Segmental applications

Segmental beam

The elevation and section of a segmental beam are shown in Fig 3. The whole structure could be made of ceramics except for the steel or FRP (fibre-reinforced plastic) tendon. Each block of ceramics could be precast as discussed earlier. The blocks could be assembled into a beam structure by joining the components together through shear keys and stabilized through the induced compressive stresses produced by the tendon. The aim of this application is to make a long-span beam with high durability. To assess this application quantitatively, a comparison with a prestressed concrete beam was made as follows.

The model is shown in Fig 4. Assuming the density of ceramics to be the same as that of concrete, the same structural dimensions are used in the analysis. The analytical assumptions are as follows:

- There is no reinforcement except a steel or FRP tendon, which can be used to cancel the effect of a vertical load. The materials are not loaded beyond the elastic range and hence can be considered as elastic. It is also assumed that there is no tensile stress on any section.
- Although there is a minimum allowable spacing between tendons in the section, it is neglected in order that simple comparisons can be made between concrete and ceramics.
- Material strength can be used as the allowable maximum stress.
- The 'load balancing method' can be adopted. An upward uniform load of the tendon can balance out the dead load of the beam. In this case, the live load cannot be cancelled by the upward uniform load of the tendon because the live load cannot always exist on the structure.
- The maximum deflection is restricted to less than L/300, where L is the span.

With these assumptions, the maximum span of the beam with no tensile stress on its section was calculated (see Appendix 1). Results for ceramic beams and concrete beams are shown in Fig 5. Although the effect of ceramics is apparent, the results obtained are much lower than had been expected, especially for glass-ceramics. This is because the maximum span is governed by beam deflection. Although the compressive strength of ceramics is 30~50 times that of concrete, the Young's modulus of the former is only about 3~10 times the latter. An optimum design is one where the maximum stress at maximum allowable deflection is just under the allowable stress. The maximum stress on the ceramics is much lower than the material strength, but the maximum stress on the concrete section is almost the same as the material strength, so the concrete beam is closer to
Structural systems made from ceramics

Concrete
L=26m

Glass Ceramics
L=36m

High performance Ceramics
L=61m

Fig 5 Maximum span

achieving an optimum design. However, in some applications, some requirements (such as maximum span) preclude an optimum design and a ceramic beam could be used.

It is interesting to find the optimum design condition mentioned in terms of material properties. This design condition in our analysis could be expressed by the following equation (see Appendix 1):

\[
\frac{\sigma_c}{E} = \sqrt{\frac{1}{3900}} \times \frac{d}{ab} \times \frac{q_{dl}}{q_c}
\]

where \(\sigma_c\) is the compressive strength, \(E\) is Young's modulus, \(d\) and \(b\) are the depth and width of the cross section, \(a\) is the rise of the tendon and \(q_{dl}\) is dead load. By using this equation, the optimum ratio of compressive strength to Young's modulus can be calculated as follows:

- Glass-ceramic beam: \(\frac{\sigma_c}{E} = \frac{1}{4800}\) (2.1)
- High-performance ceramic beam: \(\frac{\sigma_c}{E} = \frac{1}{5900}\) (2.2)
- Concrete beam: \(\frac{\sigma_c}{E} = \frac{1}{850}\) (2.3)

Also, the same ratio can be calculated from the actual material properties (see Table 1):

- Glass-ceramic beam: \(\frac{\sigma_c}{E} = \frac{1}{60}\) (3.1)
- High-performance ceramic beam: \(\frac{\sigma_c}{E} = \frac{1}{200}\) (3.2)
- Concrete beam: \(\frac{\sigma_c}{E} = \frac{1}{750}\) (3.3)

Comparison of both values for each material shows that concrete is closer to the optimum ratio than ceramics. This ratio may become a useful index for ceramic material design.

Segmental shell

The shapes of the shell and the components are shown in Fig 6. These components are made from ceramics only. Each component can be precast by pouring the molten ceramics into moulds of the appropriate shape. They can be assembled into shell structures by joining the components together through shear keys. By applying prestressing (eg on the vertex of the shell roof: tension column), this structural system could become stable because of the induced compressive stresses. Thus, the ceramic shell is under compressive membrane stress, but there is still tensile stress due to local bending moment.

Several possible methods for reducing local bending are:

- casting some members between the tension column and the ceramic shell to break up the concentrated load;

Composite applications

Composite beam

The section of a composite beam is shown in Fig 7. Ceramics could be used in the upper flange of the steel I-beam. The beam can be precast by pouring the molten ceramics into a thin steel channel at the upper flange to make a stiff and lightweight composite beam to be used in steel structures. To assess the application quantitatively, the following comparison with a pure steel beam was made.

For comparison, it is necessary to analyse a composite beam with the same weight as a pure steel beam (heavy weight can be deleterious to steel structures). To obtain the flexural stiffness \(EI\) of the composite beam, the upper flange...
Although the effect of ceramics on $E_I$ is apparent, the results obtained are much lower than had been expected, particularly for glass-ceramics. The values of $Mu$ are also lower than expected, particularly for high-performance ceramics. This is because the maximum compressive stress of ceramics is much lower than the material strength in both composite beams, while the steel yields completely. In other words, the flexural strength of composite beams is limited by the strength of steel, which is much lower than for ceramics.

**Composite wall**

It is possible to expand the composite beam application to a composite-wall application. This composite wall may be used in a 'Mega' structure (Fig 8). Mega-columns and mega-beams have box-shape sections with flanges composed of composite wall. The manufacturing process of the composite wall is the same as that of the previous composite beam. Mega-columns and mega-beams may be assembled by joining each unit of composite wall through steel ribs, which could also be used to resist local bending.

**Partial applications**

**Flat-plate reinforcement**

So far, several applications on a whole structure or a whole member have been discussed. In this section, the partial application of SFRC in conventional structural systems is discussed.

SFRC are used at a flat plate shown in Fig 9. Ceramics can be placed at the bottom of the slab to make a high-shear-resistant capital in a flat-plate structure to resist loading from the column. Under gravity load, a compressive-shear-stress state exists. Owing to the high ratio of compressive strength to density, ceramics are very effective materials for this application. However, for seismic loading, a tensile-shear-stress state can also exist at the bottom of the slab, so tensile stresses must be considered in this application.

**Beam-column joint reinforcement**

Next the partial application of SFRC at the joint in a frame structure is considered. The elevation and the perspective are shown in Fig 10. Cubic ceramics precast with steel reinforcement may be set at the joint to make a rigid joint. Little attention has been given to the design of joints in reinforced concrete structures although joints are often the weakest links in a structural system. Also, the strength of the joints should not normally govern the strength of structures. In particular, with the recent increase in the use of high-strength reinforcement and concrete, higher stiffnesses and strengths are required in beam-column joints. In the beam-column joint, a compressive strut is formed to balance the bending moment; ceramics can be effective in this part. However, since tensile stresses also occur at the joint, they must be considered in this application.
Structural systems made from ceramics

Fig 11 Lunar base

Special applications
So far, structural systems making use of the mechanical properties of advanced ceramics under ordinary environments have been considered. However, other properties of advanced ceramics such as the thermal and chemical properties, are also outstanding, and the lunar base is an example of an application where they can be used to advantage. Many feasibility studies for a lunar base have been made by space researchers and structural engineers. A lunar base would experience very large temperature variations, from 13°C (279°F) during the day to -190°C (-310°F) at the end of the lunar night, as well as being subjected to cosmic radiation and solar wind. In the absence of a protective atmosphere, bombardment by micrometeorites could also cause problems. Under the high vacuum and anhydrous conditions, the chemical stability and strength of some materials would be significantly affected. The durability of materials in the demanding lunar environment is a major design consideration.

Appendix 1: Maximum span in segmental beams

By using the ‘Load balancing method’,

$$L = \sqrt{\frac{8q_{DL}A}{q_{LL}}}$$

(A.1)

where \(q_{DL}\) is dead load (Nm\(^{-1}\)), \(L\) is the span (m), \(q_p\) is the prestress (Pa), \(A\) is the cross sectional area (m\(^2\)), and \(a\) is the rise of the tendon (m). This means that the tendon can provide an upper uniform stress to balance out the dead load of the beam.

The bending moment (Nm\(^{-1}\)) given by a live load is

$$M_{LL} = \frac{q_{LL}L^2}{8}$$

(A.2)

where \(q_{LL}\) is the live load (Nm\(^{-1}\)). Tensile stress at the bottom fibre of a section due to a live load is

$$\sigma_{LL} = \frac{M_{LL}}{Z}$$

(A.3)

where \(Z\) is a geometric moment of area.

Substituting Equations (A.1) and (A.2) into (A.3) gives

$$\sigma_{LL} = \frac{6a_{DL}q_{LL}}{dq_{DL}}$$

(A.4)

where \(d\) is the depth of the beam section.
To obtain zero stress at the bottom fibre of a section, \( \sigma_p \) is made equal to all. Thus

\[
q_{LL} = \frac{dq_{DL}}{8a}
\]  
(A.5)

This is the condition in which there is a compressive stress \( \sigma_p \) at any section for \( q_{DL} \), and there is a zero stress at the bottom fibre of a section and a compressive stress \( 2\sigma_p = \sigma_L + \sigma_{LL} \) at the top fibre of a section for \( q_{DL} + q_{LL} \). To prevent fracture by crushing, the following condition at the top fibre of a section must be satisfied.

\[
2\sigma_p < \sigma_c \quad \text{(A.6)}
\]

where \( \sigma_c \) is compressive strength.

To restrict a large deflection, there is the condition:

\[
\delta = \frac{5q_{LL}L^4}{384EI} \leq \frac{L}{300} \quad \text{(A.7)}
\]

where \( \delta \) is the vertical deflection of the beam, \( E \) is Young’s modulus and \( I \) is the moment of second order.

Substituting Equation (A.1) into (A.7), gives

\[
\sigma_p \leq \left( \frac{dq_{DL}E^3}{31250ba} \right)^{1/3} \quad \text{(A.8)}
\]

where \( b \) is a width of the beam section.

Equations (A.6) and (A.7) are the conditions that can cover the design conditions of maximum allowable stress and deflection. By using those equations maximum \( \sigma_c \) can be obtained. Substituting the \( \sigma_p \) obtained into Equation (A.1), the maximum span \( L \) can be obtained. Existing maximum compressive stresses at the top fibre of ceramics and concrete are as follows (the values of \( q_{DL} \) and \( q_{LL} \) in Fig 4 are used):

- Concrete: 37 Mpa <~ 40 Mpa
- Glass-ceramics: 73 Mpa <~ 1300 Mpa
- High-performance ceramics: 209 Mpa <~ 2000 Mpa

An optimum design is one with the maximum stress at maximum allowable deflection just under the allowable stress. This optimum design condition could be expressed by

\[
\sigma_L = \frac{8}{3} \frac{d}{E} \frac{q_{DL}}{\sigma_c} \quad \text{(A.9)}
\]

where \( \sigma_L \) is the stress at the critical section.

Appendix 2: Flexural stiffness and strength in composite beam

To calculate the flexural stiffness in a composite beam, the method of equivalent section was adopted. The upper flange of the composite beam may work as an axial member for compressive force. By equating the axial stiffness of the upper flange in the composite beam to that in the equivalent section of steel (H-800 x 300 x 16 x 32), the equivalent steel section with flexural stiffness almost equal to that of the composite section can be obtained. The flexural stiffness of this equivalent section can be calculated by usual methods. The results are as follows:

- Glass-ceramics (composite 1): \( I = 3.61 \times 10^8 \text{mm}^4 \)
- High-performance ceramics (composite 2): \( I = 5.93 \times 10^8 \text{mm}^4 \)
- Pure steel section (H-800 x 300 x 16 x 32): \( I = 3.36 \times 10^9 \text{mm}^4 \)

Since the compressive strength of ceramics is much higher than that of steel, the neutral axis at an actual ultimate stress distribution is on the ceramic section (Fig 12), resulting in the tensile stress on the ceramic section. This may not be a desirable situation, so, as the flexural strength of the composite beam, the critical strength in which the neutral axis is at the interface between ceramics and steel was used to obtain no tensile stress on the ceramic section. This critical strength may be almost the same as that of actual ultimate flexural strength and could be conservative. As a result, the flexural strength when using high-performance ceramics is the same as that for glass-ceramics. The flexural strength of steel can be calculated such that \( Mu = \sigma_TZ_p \), where \( Mu \) is a plastic moment, \( \sigma_T \) is a tensile strength and \( Z_p \) is a plastic moment of first order. The results are

- Steel: \( Mu = 9.54 \times 220 = 2.1 \text{ MNm} \)
- Glass-ceramics (composite 1): \( Mu = 2.58 \text{ MNm} \)
- High-performance ceramics (composite 2): \( Mu = 2.58 \text{ MNm} \)