Practice and testing of stone cladding in Hong Kong

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Introduction

As a nature material, its structural properties vary between different stone type, between different colors and cut orientation in the same stone type, and even throughout the medium of the same type and same color and same bed of the same quarry. The magnitudes of these properties and the range of their variability shall be quantified with tests.

And also, because its breath of visual character often reflects a wide variability in engineering performance, particularly strength and durability. Strength can vary by serve orders of magnitude between different types of stones.

Keyword : Stone, cladding, test method

Typical variation in stone strength

Stone type	Flexural strength (MPa)	Compressive strength (MPa)
Granite	8 ~ 20	120 ~ 240
Sandstone	2.5 ~ 15	30 ~ 200
Limestone (High)	6 ~ 15	55 ~ 180
Limestone (Low)	2 ~ 10	10 ~ 90

Physical requirements in ASTM

	Granite	Limestone	Quartz-Based stone
Standard	ASTM C615	ASTM C568	ASTM C616
Absorption, max, %	0.40	12 (low-density) 7.5 (medium-density) 3 (high-density)	8 (sandstone) 3 (Quartzitic sandstone) 1 (Quartzite)
Density, min, kg/m^3	2560	1760 (low-density) 2160 (medium-density) 2560 (high-density)	2003 (sandstone) 2400 (Quartzitic sandstone) 2560 (Quartzite)
Compressive strength, min, MPa	131	12 (low-density) 28 (medium-density) 55 (high-density)	27.6 (sandstone) 68.9 (Quartzitic sandstone) 137.9 (Quartzite)
Modulus of rupture, min, MPa	10.34	2.9 (low-density) 3.4 (medium-density) 6.9 (high-density)	2.4 (sandstone) 6.9 (Quartzitic sandstone) 13.9 (Quartzite)
Flexural strength, min, MPa	8.27		

Need for stone testing

i) New stone without available information.
ii) As supplier only provide some mechanical properties, strength of the stone in actual project need to be verified in order to confirm its suitability.
iii) Stone on an existing building appear to have failure by cracking at the fixing points. In particular, strength and anchor capacity has to be checked.
iv) Full scale is recommended to test the fully stimulate job condition and details.
v) Demand a consistent strength stone throughout the project. Production test is needed to form part of the quality assurance during construction.

Stone test standard

ASTM test standard

ASTM standard	Subject
C 97	Absorption and Bulk Specific Gravity of Dimension Stone
C 99	Modulus of Rupture of Dimension Stone
C 170	Compressive strength of Dimension Stone
C 295	Guide to Petrographic Examination of Aggregates for Concrete
C 880	Flexural Strength of Dimension Stone
C 1201	Structural Performance of Exterior Dimension Stone Cladding Systems by Uniform Static Air Pressure Difference
C 1352	Flexural Modulus of Elasticity of Dimension Stone
C 1354	Strength of Individual Stone Anchorage in Dimension Stone

BS EN test standard

BS EN standard	Subject
EN 1925	Natural stone test methods – Determination of water absorption coefficient by capillarity
EN 1926	Natural stone test methods – Determination of compressive strength
EN 1936	Natural stone test methods – Determination of real density and apparent density and of total and open porosity
EN 12372	Natural stone test methods – Determination of flexural strength under concentrated load
EN 12407	Natural stone test methods –Petrographic Examination
EN 13161	Natural stone test methods – Determination of flexural strength under constant moment
EN 13364	Natural stone test methods – Determination of the breaking load at dowel hole
EN 13755	Natural stone test methods – Determination of water absorption at atmospheric pressure

- Among the ASTM and BS EN standard, they nearly covers all the similar physical properties, except
- ASTM C295 is test method for Aggregates for Concrete while BS EN 12407 is for natural stone, and
- ASTM C1354 is a general test method for all anchorage type while BS EN 13364 is for dowel hole only.
- It is more common to adopt ASTM standard in stone testing in Hong Kong.

PNAP 59 – Cladding

Tests on Stone Cladding Panels

6. Stone cladding is a natural material. The mechanical properties, physical properties and chemical properties can vary considerably between different types and grades of stones. Tests on stone cladding panels are required to be carried out to verify the characteristic strengths adopted in the design and to form part of quality assurance during construction. The characteristic strengths shall be not less than three times that of the designed strengths used.

7. When stone cladding is to be used, the following tests are required to be carried out for each type of stone :

(a) flexural strength test of dimension stone to ASTM C880 – Standard Test Method for Flexural Strength of Dimension Stone or to BS EN12372 – Natural Stone Test Methods, Determination of Flexural Strength under Concentrated Load or to other appropriate equivalent standards; and

(b) strength test of individual stone anchorage to ASTM C1354 – Standard Test Method for Strength of Individual Stone Anchorages in Dimension Stone or to other appropriate equivalent standards.

- Among the tests for different physical properties, flexural strength and anchorage capacity are the most important and the minimum requirements to be adopted in stone testing in Hong Kong.

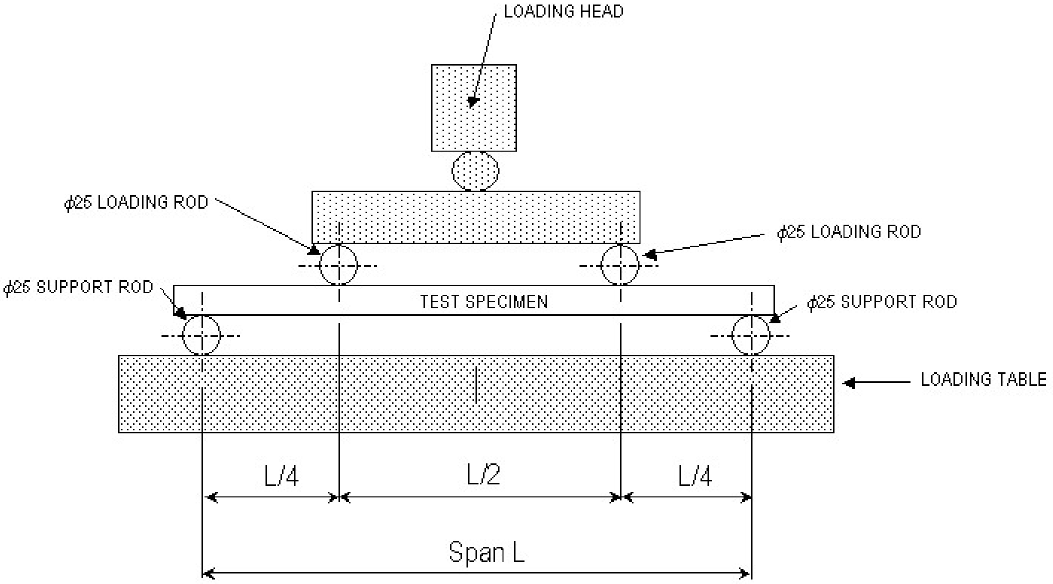
By means of actual test results, this talk will discuss:

i) The test method of ASTM C880 (flexural strength) and ASTM C1354 (Strength of Individual Stone Anchorage in Dimension Stone).
ii) The physical perimeter causes for variation in the test result.
iii) Discrepancy between adopted design calculation and test result for anchorage capacity.
iv) Evaluation of the stone cladding system under full size panel test.

Flexural strength test (ASTM C880)

ASTM C880 is a four point bending test to create a purely flexural tension-stress failure at the extreme of the tension face. The stress mechanics measured in this test are similar to those created in the midspan of the cladding between the anchorages. The test result is useful to check the flexural stress at midspan under uniform distributed design load such as design wind load.

Test arrangement



Test rig

Test Specimens

If the job thickness is not specified, the requirements of test specimen shall be that:

i) A minimum of five (5) specimens shall be tested for each sample in each condition of test;

ii) The test specimens shall be 102 mm (wide) × 32 mm (thick) × 381 mm (long) with a test span of 318 mm;

iii) The sides of the specimens shall be approximately at right angles with the top and bottom surfaces;

iv) The specimens shall have a fine abrasive finish on the planes perpendicular to the applied load (i.e. the top and bottom surfaces) and a fine saw finish on the other four planes (i.e. the edges).

If the job thickness is specified, the requirements of test specimen shall be that:

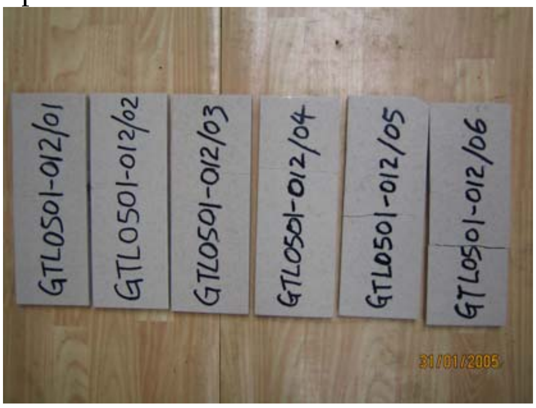
i) The actual measured thickness of the specimens should be rounded off to the nominal thickness. The span shall be 10 times the nominal thickness;

ii) The specimen length shall be not less than 51 mm and not more than 102 mm greater than the span as tested;

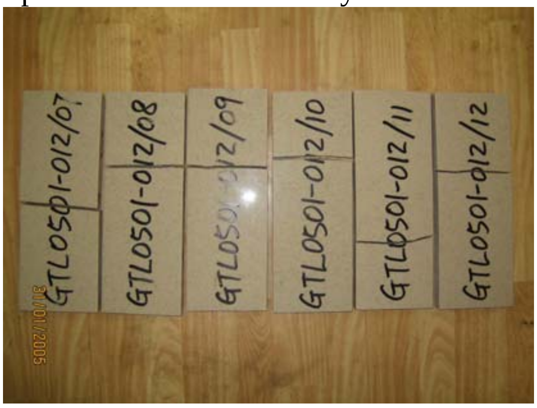
iii) The width of the specimens shall be 102 mm where the thickness is less than 68 mm, or 1.5 times the thickness where the thickness is greater than 68 mm.

Sample of tested specimen

Specimens tested under wet condition



Specimens tested under dry condition



The physical perimeter causes for variation in the test result.

i) Wet and dry conditioning

	Flexural strength, MPa		
Stone	Wet	Dry	% Difference
Aran Gold	9.38	11.76	25.4
Bethel White	12.69	14.67	15.6
Black Green	10.26	15.04	46.6
Chunky Ash	17.15	22.04	28.5
Giallo Cecilia	9.45	12.00	27.0
Raw Silk	7.85	10.20	29.9

ii) Stone rift orientation to direction of test load

	Flexural strength, MPa					
	Wet			Dry		
Stone	Parallel	Perpendicular	%	Parallel	Perpendicular	%
Giallo Dorada	8.84	7.85	-11.2	9.76	9.35	-4.2
Giallo S.F. Real	8.67	8.76	1.0	8.55	9.23	8.0
Golden Moon	9.37	8.77	-6.4			
Peitrabella (Limestone)	6.48	6.08	-6.2	9.72	9.45	-2.8
木紋砂岩 (Sandstone)	9.63	13.74	42.7			

iii) Stone finish

Stone	Finish	Flexural strength	Finish	Flexural strength	%
Absolute Black	Polished	25.94	Flamed	28.33	9.2
Giallo Cecilia	Honed	7.40	Polished	8.07	9.1
Giallo Dorada	Tapestry	8.89	Bush-hammered	9.86	10.9
Impala Black	Polished	16.41	Honed	16.60	1.2

iv) Test specimen size

The test results also vary in different surface area under maximum-stress. Larger region of the test specimen is at the maximum-stress, more opportunity or potential exists for a natural weakness of feature to occur in that region and lead to a lower flexural strength.

Stone	Specimen size	Flexural strength	Specimen size	Flexural strength	%
Giallo St. Nicholas	102x380x30	7.59	300x750x30	6.44	-15.2
China Grey 633	102x380x30	10.28	300x900x30	8.92	-13.2

The failure area in C880 sample is quite small in comparison with the failure area that will exist for a full panel, modified sample size to actual job span and thickness is recommended.

Discussion:

i) The variations due to wet/dry conditioning, cut orientation and finish are addressed in the standard. The combination of test groups shall be correctly selected by the designer/engineer depends on the stone historical tests and job condition (finishes and cut orientation used in the job case).

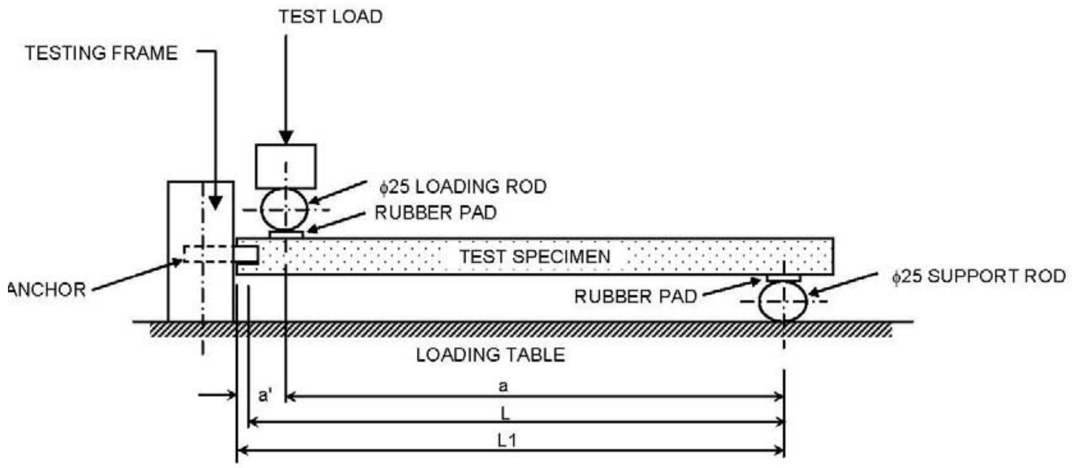
ii) For the variation due to test specimen size, a modification to job size should be considered to facilitate the project-specific conditions.

Stone anchorage test (ASTM C1354)

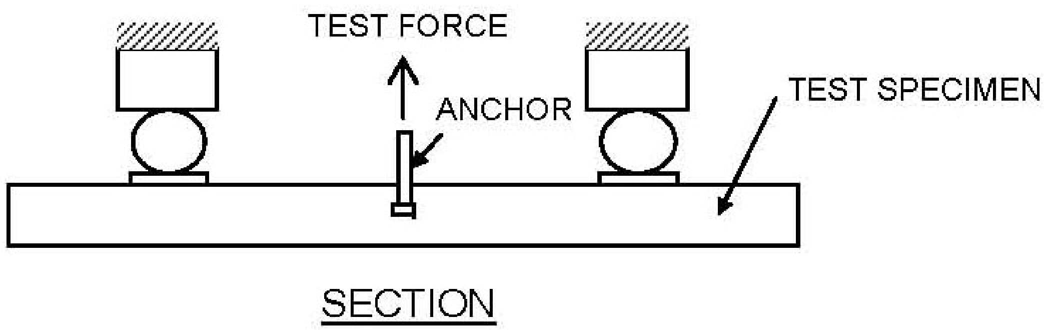
The stone capacity of an anchor is difficult to accurately predict mathematically as relative stiffness of stone, anchor, infil material and back-up control how much of the anchorage device is actually resisting load is difficult to determine.
Anchor tests are procedures specifically conceived and design to isolate and quantity the capacity of each individual stone anchorage in the configuration to be installed specified for the project.

Test arrangement

Kerf anchor type



Back anchor type



Test rig

Kerf anchor type

Back anchor type

Test Specimens

The test specimen size requirements for kerf anchorage system shall be that:

a) The specimen width shall be 305 mm;
b) The specimen length shall be half of the anchor embedment plus 8 ~ 10 stone thickness plus 25 ~ 50 mm.
c) The sides of the specimens shall be approximately at right angles with each other.

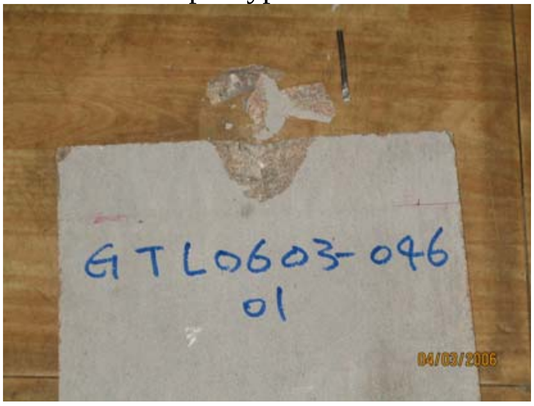
The test specimen size requirements for back anchorage system shall be that:

a) The specimen size shall be 305 mm(W) x 305 mm(L);
b) The sides of the specimens shall be approximately at right angles with each other;

Sample of tested specimen

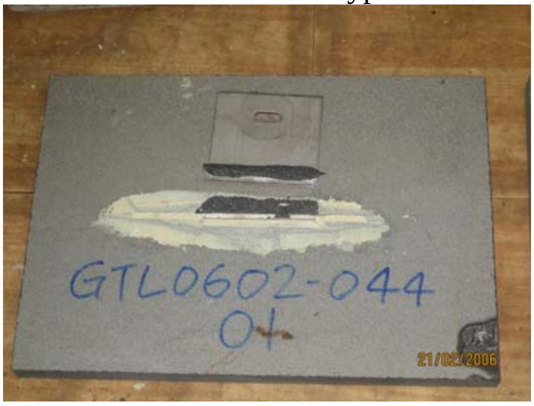
Kerf anchor – clip type

Kerf anchor – pin type

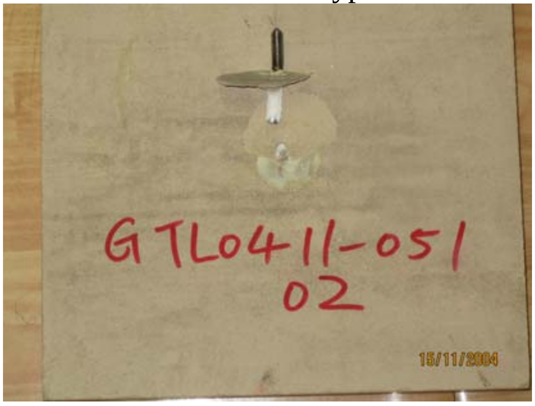


Kerf anchor – L-shape type

Back anchor – Bent sheet type



Back anchor – Bent bolt type



Back anchor – Fischer Bolt

Some physical perimeter cause for variation in the test result.

i) Wet and dry conditioning

In ASTM C1354, wet sample group must be tested. Test of dry sample group is subjected to the designer's option. The option is usually depended on the test result of the Flexural strength if the dry sample group in flexural strength test is much lesser than the wet sample group.

ii) Stone rift orientation to direction of test load

In the job case, the cut orientation is governed by the architectural pattern of the stone cladding. Therefore, same cut orientation will be adopted throughout the project and the effect of rift orientation to direction of test load is not occurred.
If the job slab is cut randomly, the effect of rift orientation to direction of test load in the anchorage test should be addressed.

iii) Test load direction

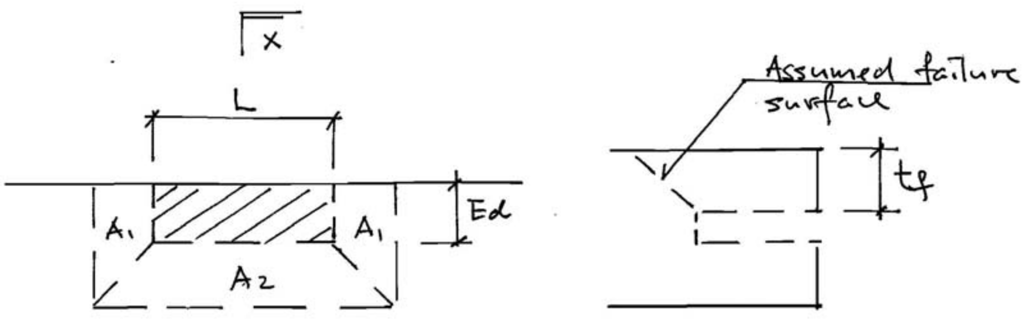
In ASTM C1354, one group of specimen shall be tested with the load applied outward, and one group with the load applied inward. However, at the designer's option, only one direction may be tested when it is apparent that a direction is the most critical based on the combination of greater load and lower strength.

iv) Infil material in slot, drilled hole for kerf or back anchorage

Anchor type	Nominal bracket size	Infil material	Anchorage Load, kN
Kerf	22x200x4mm split bracket, 120 mm lg	Epoxy	6.06
		Sealant	3.79
		% difference	-37.5
Back	18x180x4 mm bent bracket, 100 mm lg	Epoxy	7.58
		Sealant	0.94
		% difference	-87.6

Discrepancy between adopted design calculation and test result for anchorage capacity

Comparison design calculation and test result for different bracket lengths in Kerf Anchor
Traditional design calculation



L = Bracket length
Ed = Bracket embedment
tf = Kerf thickness at failure side

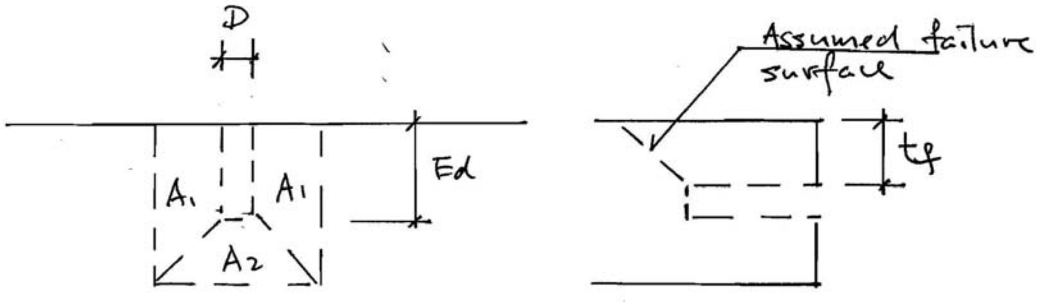
Assumed failure area
A_1 = 0.5 x (2 x Ed + tf) x tf / $\cos 45^o$
A_2 = (tf + L) x tf / $\cos 45^o$
Total failure area,
A = 2 x A_1 + A_2
= (2 x Ed +2 x tf + L) x tf / $\cos 45^o$
Anchorage capacity
R = strength x A

Test specimen
Type = L-shape kerf anchor
Ed = 20 mm
tf = 12 mm

Bracket length, mm	25	50	100	300
Test result, N	1864	1965	2860	4086
Calculated value, N	1864	2388	3435	7624
% different	---	21.5	20.1	86.6

Remark : The strength in the calculation is adopted from the test result of 25 mm long bracket.

Comparison design calculation and test result for different embed in Kerf Pin Anchor
Traditional design calculation



D = Pin diameter
Ed = Bracket embedment
tf = Kerf thickness at failure side

Assumed failure area
A_1 = 0.5 x (2 x Ed + tf) x tf / cos45^o
A_2 = (tf + D) x tf / cos45^o
Total failure area,
A = 2 x A_1 + A_2
= (2 x Ed +2 x tf + D) x tf / cos45^o
Anchorage capacity
R = strength x A

Test specimen
Type = Pin kerf anchor
D = 5 mm
tf = 12.5 mm

Embedment, mm	20	25	30	35
Test result, N	1586	1670	1702	1654
Calculated value, N	1586	1810	2037	2263
% different	0.0	8.4	19.7	36.8

Remark : The strength in the calculation is adopted from the test result of 20 mm embedment depth.

Discussion:
i) The variations due to wet/dry conditioning, cut orientation and finish are addressed in the standard. The combination of test groups shall be correctly selected by the designer/engineer depends on the stone historical tests and job condition (finish and cut orientation used in the job case).
ii) The infil material is critical to the test results.
iii) The relationship between length of the kerf bracket and embedment depth of pin anchorage is not directly linear and the recent design calculation method does not correlate the actual test results.

Full size panel test (ASTM C1201)

The stone cladding and its anchorages require higher ultimate resistance than glass and metal external wall because the stone has a greater range of uncertainties. After individual element test, the complete actual-size panel with its individual anchorages shall be accurately configured for testing to simulate job condition and details to elevate the overall performance of stone wall. The test as described in ASTM C1201 provides the test method to determine the structural performance of stone cladding system under positive and negative uniform static pressure using a test chamber.

Test arrangement

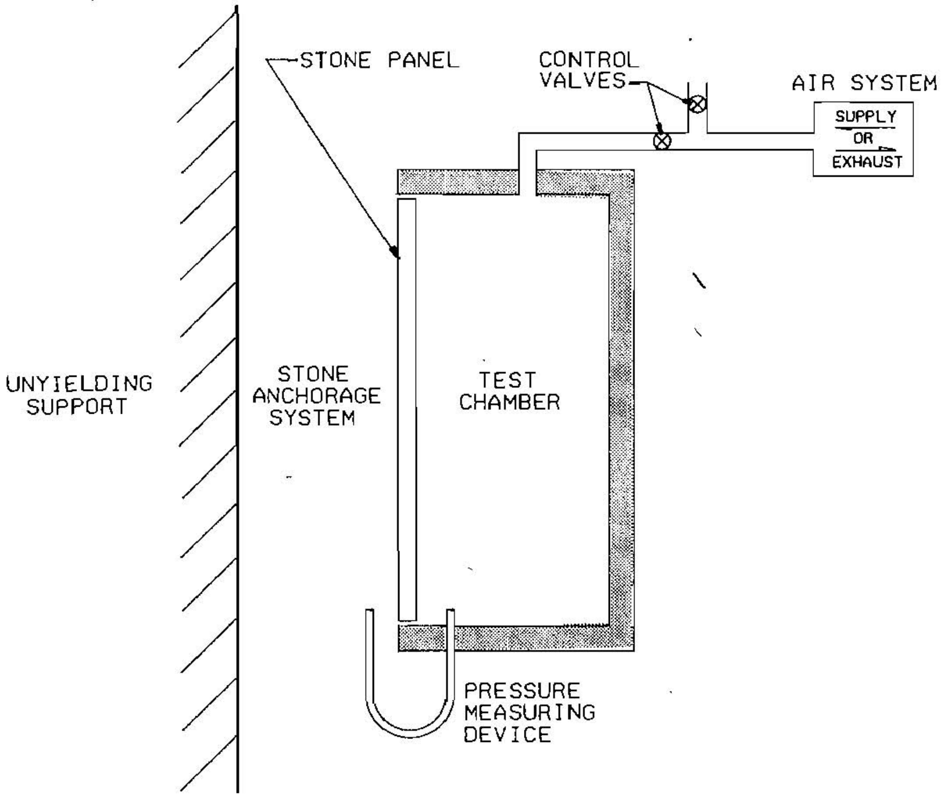
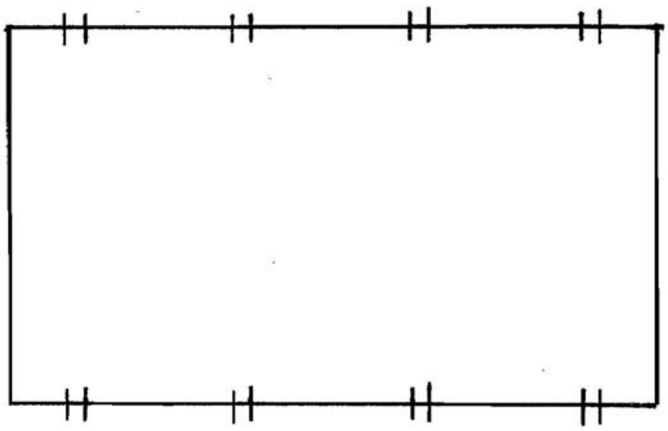


FIG. 1 General Arrangement of Testing Apparatus

Test Setup

Comparison design calculation and test result.

Configuration of tested sample



Size : 1650 mm wide x 950 mm height x 25 mm nominal thick
Anchorage : 8 numbers pin anchorages at top & bottom kerf
Anchorage type : Double 4 mm dia stainless steel pin with 18 mm nominal embedment
Design pressure : 3.08 kPa

		Test results			
	Design value	Mean/ Ultimate	Deviation	Characteristic strength	FOS
Flexural strength, MPa	3.33	15.88	1.57	10.54	3.17
Anchorage capacity, kN	0.30	2.06	0.22	1.31	4.37
Pressure, KPa	3.08	6.25	(Initial anchorage failure)		2.03
		8.25	(Ultimate panel failure)		2.68

Discussion:

i) The safety factor of the overall stone cladding system is lesser than the individual physical properties.

ii) The difference is more critical in the anchorage location.

iii) The failure mode (panel or anchorage) could act as an important indicator of the critical portion of the stone cladding in the actual job condition.