國立雲林科技大學
98 學年度博士班招生考試試題

所別：工程科技研究所
科目：工程數學 (1)

本試題共 6 題，共計 100 分，請依題號作答並將答案寫在答案卷上，違者不予計分。

1. Solve the general solution of differential equations: $\dfrac{dy}{dx} = y+1$ (本題 10 分)
2. Solve the general solution of differential equations: $[x^2D^2 - 5xD + 8]y = 2\ln x$.

   [Note: $D^n y = y^{(n)} = \dfrac{d^n}{dx^n} y$] (本題 10 分)
3. Let $A = \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}$, (本題共 30 分)

   (1) find the determinant of A, $|A| = ?$ (5 分)

   (2) find the eigenvalues and eigenvectors of the matrix A, (5 分)

   (3) find an orthogonal matrix Q and Q^{-1}, then diagonalize the matrix A, (5 分)

   (4) $A^{100} = ?$ (5 分)

   (5) If $X(t) = \Omega(t)\,C$ is the general solution of the system $X' = A\,X$, find the fundamental matrix $\Omega(t) = ?$ (10 分)

4. Use the Laplace transform to solve the integral equation:

   $y(t) = 3 + \int_0^t y(\alpha)\cos[2(t-\alpha)]\,d\alpha$ (本題 15 分)
5. Use the Laplace transform to solve the initial value problem: $\begin{cases} x' - 2y' = 1 \\ x' - x + y = 0 \end{cases}$,

   $x(0) = y(0) = 0$. (本題 15 分)
6. If $f(x) = x^2$ for $0 \le x \le 2$, find its (a) Fourier cosine series and (b) Fourier sine series. (本題 20 分)

國立雲林科技大學
98學年度博士班招生考試試題

所別：工程科技研究所、電子工程系
科目：工程數學 (2)

1. (10%) Solve $(y^2 - y)dx + xdy = 0$ with $y(1) = 2$

2. (15%)Find the integrating factor and solve :

$$2\sin ydx + \cos ydy = 0,\ y(0) = \frac{\pi}{2}$$

3. (10%) Solve the general solution $y'' + 5y' + 6y = e^{-2x}$

4. (15%) Find the eigenvalues and eigenvector of the matrix

$$A = \begin{bmatrix} 3 & 0 & 0 \\ 0 & 4 & \sqrt{3} \\ 0 & \sqrt{3} & 6 \end{bmatrix}$$

5. (15%)Evaluate the integral

$$\oiint_s [(y+z)dydz + (z+x)dzdx + (x+z)dxdy],\ where\ \ s: x^2 + y^2 + z^2 = 1.$$

6. (15%) If $f(x) = 1 - \frac{x}{2}$, $0 \le x \le 2$, (a) find the Fourier coefficients (with full- range expansions). (b) Find the Fourier cosine series (with half-range expansions).

7. (10%)Find the integral : $\int_0^\infty \frac{\cos x\omega}{1+\omega^2} d\omega$.

8. (10%) Let $\bar{F}$ be a continuous vector field with continuous first and second partial derivatives. Prove that $\nabla \cdot (\nabla \times \bar{F}) = 0$.

國立雲林科技大學
98 學年度博士班招生考試試題

所別：工程科技研究所、環安系
科目：工程數學 (3)

1. Solve the equation：$\dfrac{dy}{dx} = 8x^3y^2$ (10 points)

2. Solve the equation：$y'' - 8y' + 16y = 8\sin(2x) + 3e^{4x}$ (10 points)

3. Solve the equation：$y'' + 4y = f(t)$；$y(0) = 1,\ \ y'(0) = 0$；

$$f(t) = \begin{cases} 0 & if \ \ 0 \le t < 4 \\ 3 & if \ \ \ \ t \ge 4 \end{cases}$$ (10 points)

4. 試以 Taylor series method 求解下列聯立方程式之前 4 個非零項：

$$\begin{cases} \dfrac{dx}{dt} = xy + t, & x(0) = 1 \\ \dfrac{dy}{dt} = ty + x & y(0) = -1 \end{cases}$$ (10 points)

5. 某溫度計從原來 30℃的房間拿到室外，3 分鐘後，其讀數為 24℃；再過 3 分鐘後，則為 22℃。試問室外溫度多少℃？ (10 points)

6. A random sample of 50 suspension helmets used by motorcycle riders and automobile race-car drivers was subjected to an impact test, and on 18 of these helmets some damage was observed. Find a 95% two-sided confidence interval on the true proportion of helmets of this type that would show damage from this test. (10 points)

7. A bearing used in an automotive application is supposed to have a nominal inside diameter of 1.5 inches. A random sample of 25 bearings is selected and the average inside diameter of these bearings is 1.4975 inches. Bearing diameter is known to be normally distributed with standard deviation $\sigma = 0.01$ inch.
   (a) Test the hypotheses H_0: $\mu = 1.5$ versus H_1: $\mu \neq 1.5$ using $\alpha = 0.01$. (10 points)
   (b) Compute the power of the test if the true mean diameter is 1.495 inches. (10 points)

8. In a random sample of 85 automobile engine crankshaft bearings, 10 have a surface finish roughness that exceeds the specifications. Does this data present strong evidence that the proportion of crankshaft bearings exhibiting excess surface roughness exceeds 0.10? State and test the appropriate hypotheses using $\alpha = 0.05$. (10 points)

9. A rivet is to be inserted into a hole. A random sample of $n = 15$ parts is selected, and the hole diameter is measured. The sample standard deviation of the hole diameter measurements is $s = 0.008$ millimeters. Construct a 99% lower confidence bound for σ^2. (10 points)

國立雲林科技大學
98學年度博士班招生考試試題

所別：工程科技研究所、環安系
科目：工程數學 (3)

$$\Phi(z) = P(Z \le z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}u^2}\, du$$

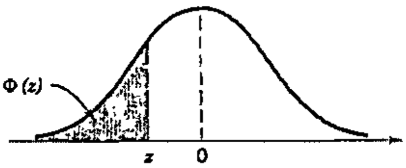


Table II Cumulative Standard Normal Distribution

z	−0.09	−0.08	−0.07	−0.06	−0.05	−0.04	−0.03	−0.02	−0.01	−0.00
−3.9	0.000033	0.000034	0.000036	0.000037	0.000039	0.000041	0.000042	0.000044	0.000046	0.000048
−3.8	0.000050	0.000052	0.000054	0.000057	0.000059	0.000062	0.000064	0.000067	0.000069	0.000072
−3.7	0.000075	0.000078	0.000082	0.000085	0.000088	0.000092	0.000096	0.000100	0.000104	0.000108
−3.6	0.000112	0.000117	0.000121	0.000126	0.000131	0.000136	0.000142	0.000147	0.000153	0.000159
−3.5	0.000165	0.000172	0.000179	0.000185	0.000193	0.000200	0.000208	0.000216	0.000224	0.000233
−3.4	0.000242	0.000251	0.000260	0.000270	0.000280	0.000291	0.000302	0.000313	0.000325	0.000337
−3.3	0.000350	0.000362	0.000376	0.000390	0.000404	0.000419	0.000434	0.000450	0.000467	0.000483
−3.2	0.000501	0.000519	0.000538	0.000557	0.000577	0.000598	0.000619	0.000641	0.000664	0.000687
−3.1	0.000711	0.000736	0.000762	0.000789	0.000816	0.000845	0.000874	0.000904	0.000935	0.000968
−3.0	0.001001	0.001035	0.001070	0.001107	0.001144	0.001183	0.001223	0.001264	0.001306	0.001350
−2.9	0.001395	0.001441	0.001489	0.001538	0.001589	0.001641	0.001695	0.001750	0.001807	0.001866
−2.8	0.001926	0.001988	0.002052	0.002118	0.002186	0.002256	0.002327	0.002401	0.002477	0.002555
−2.7	0.002635	0.002718	0.002803	0.002890	0.002980	0.003072	0.003167	0.003264	0.003364	0.003467
−2.6	0.003573	0.003681	0.003793	0.003907	0.004025	0.004145	0.004269	0.004396	0.004527	0.004661
−2.5	0.004799	0.004940	0.005085	0.005234	0.005386	0.005543	0.005703	0.005868	0.006037	0.006210
−2.4	0.006387	0.006569	0.006756	0.006947	0.007143	0.007344	0.007549	0.007760	0.007976	0.008198
−2.3	0.008424	0.008656	0.008894	0.009137	0.009387	0.009642	0.009903	0.010170	0.010444	0.010724
−2.2	0.011011	0.011304	0.011604	0.011911	0.012224	0.012545	0.012874	0.013209	0.013553	0.013903
−2.1	0.014262	0.014629	0.015003	0.015386	0.015778	0.016177	0.016586	0.017003	0.017429	0.017864
−2.0	0.018309	0.018763	0.019226	0.019699	0.020182	0.020675	0.021178	0.021692	0.022216	0.022750
−1.9	0.023295	0.023852	0.024419	0.024998	0.025588	0.026190	0.026803	0.027429	0.028067	0.028717
−1.8	0.029379	0.030054	0.030742	0.031443	0.032157	0.032884	0.033625	0.034379	0.035148	0.035930
−1.7	0.036727	0.037538	0.038364	0.039204	0.040059	0.040929	0.041815	0.042716	0.043633	0.044565
−1.6	0.045514	0.046479	0.047460	0.048457	0.049471	0.050503	0.051551	0.052616	0.053699	0.054799
−1.5	0.055917	0.057053	0.058208	0.059380	0.060571	0.061780	0.063008	0.064256	0.065522	0.066807
−1.4	0.068112	0.069437	0.070781	0.072145	0.073529	0.074934	0.076359	0.077804	0.079270	0.080757
−1.3	0.082264	0.083793	0.085343	0.086915	0.088508	0.090123	0.091759	0.093418	0.095098	0.096801
−1.2	0.098525	0.100273	0.102042	0.103835	0.105650	0.107488	0.109349	0.111233	0.113140	0.115070
−1.1	0.117023	0.119000	0.121001	0.123024	0.125072	0.127143	0.129238	0.131357	0.133500	0.135666
−1.0	0.137857	0.140071	0.142310	0.144572	0.146859	0.149170	0.151505	0.153864	0.156248	0.158655
−0.9	0.161087	0.163543	0.166023	0.168528	0.171056	0.173609	0.176185	0.178786	0.181411	0.184060
−0.8	0.186733	0.189430	0.192150	0.194894	0.197662	0.200454	0.203269	0.206108	0.208970	0.211855
−0.7	0.214764	0.217695	0.220650	0.223627	0.226627	0.229650	0.232695	0.235762	0.238852	0.241964
−0.6	0.245097	0.248252	0.251429	0.254627	0.257846	0.261086	0.264347	0.267629	0.270931	0.274253
−0.5	0.277595	0.280957	0.284339	0.287740	0.291160	0.294599	0.298056	0.301532	0.305026	0.308538
−0.4	0.312067	0.315614	0.319178	0.322758	0.326355	0.329969	0.333598	0.337243	0.340903	0.344578
−0.3	0.348268	0.351973	0.355691	0.359424	0.363169	0.366928	0.370700	0.374484	0.378281	0.382089
−0.2	0.385908	0.389739	0.393580	0.397432	0.401294	0.405165	0.409046	0.412936	0.416834	0.420740
−0.1	0.424655	0.428576	0.432505	0.436441	0.440382	0.444330	0.448283	0.452242	0.456205	0.460172
0.0	0.464144	0.468119	0.472097	0.476078	0.480061	0.484047	0.488033	0.492022	0.496011	0.500000

國立雲林科技大學
98學年度博士班招生考試試題

所別：工程科技研究所、環安系
科目：工程數學 (3)

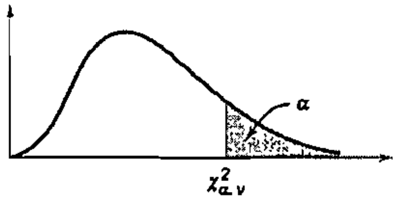


Table III Percentage Points $\chi^2_{\alpha,\nu}$ of the Chi-Squared Distribution

ν \ α	.995	.990	.975	.950	.900	.500	.100	.050	.025	.010	.005
1	.00+	.00+	.00+	.00+	.02	.45	2.71	3.84	5.02	6.63	7.88
2	.01	.02	.05	.10	.21	1.39	4.61	5.99	7.38	9.21	10.60
3	.07	.11	.22	.35	.58	2.37	6.25	7.81	9.35	11.34	12.84
4	.21	.30	.48	.71	1.06	3.36	7.78	9.49	11.14	13.28	14.86
5	.41	.55	.83	1.15	1.61	4.35	9.24	11.07	12.83	15.09	16.75
6	.68	.87	1.24	1.64	2.20	5.35	10.65	12.59	14.45	16.81	18.55
7	.99	1.24	1.69	2.17	2.83	6.35	12.02	14.07	16.01	18.48	20.28
8	1.34	1.65	2.18	2.73	3.49	7.34	13.36	15.51	17.53	20.09	21.96
9	1.73	2.09	2.70	3.33	4.17	8.34	14.68	16.92	19.02	21.67	23.59
10	2.16	2.56	3.25	3.94	4.87	9.34	15.99	18.31	20.48	23.21	25.19
11	2.60	3.05	3.82	4.57	5.58	10.34	17.28	19.68	21.92	24.72	26.76
12	3.07	3.57	4.40	5.23	6.30	11.34	18.55	21.03	23.34	26.22	28.30
13	3.57	4.11	5.01	5.89	7.04	12.34	19.81	22.36	24.74	27.69	29.82
14	4.07	4.66	5.63	6.57	7.79	13.34	21.06	23.68	26.12	29.14	31.32
15	4.60	5.23	6.27	7.26	8.55	14.34	22.31	25.00	27.49	30.58	32.80
16	5.14	5.81	6.91	7.96	9.31	15.34	23.54	26.30	28.85	32.00	34.27
17	5.70	6.41	7.56	8.67	10.09	16.34	24.77	27.59	30.19	33.41	35.72
18	6.26	7.01	8.23	9.39	10.87	17.34	25.99	28.87	31.53	34.81	37.16
19	6.84	7.63	8.91	10.12	11.65	18.34	27.20	30.14	32.85	36.19	38.58
20	7.43	8.26	9.59	10.85	12.44	19.34	28.41	31.41	34.17	37.57	40.00
21	8.03	8.90	10.28	11.59	13.24	20.34	29.62	32.67	35.48	38.93	41.40
22	8.64	9.54	10.98	12.34	14.04	21.34	30.81	33.92	36.78	40.29	42.80
23	9.26	10.20	11.69	13.09	14.85	22.34	32.01	35.17	38.08	41.64	44.18
24	9.89	10.86	12.40	13.85	15.66	23.34	33.20	36.42	39.36	42.98	45.56
25	10.52	11.52	13.12	14.61	16.47	24.34	34.28	37.65	40.65	44.31	46.93
26	11.16	12.20	13.84	15.38	17.29	25.34	35.56	38.89	41.92	45.64	48.29
27	11.81	12.88	14.57	16.15	18.11	26.34	36.74	40.11	43.19	46.96	49.65
28	12.46	13.57	15.31	16.93	18.94	27.34	37.92	41.34	44.46	48.28	50.99
29	13.12	14.26	16.05	17.71	19.77	28.34	39.09	42.56	45.72	49.59	52.34
30	13.79	14.95	16.79	18.49	20.60	29.34	40.26	43.77	46.98	50.89	53.67
40	20.71	22.16	24.43	26.51	29.05	39.34	51.81	55.76	59.34	63.69	66.77
50	27.99	29.71	32.36	34.76	37.69	49.33	63.17	67.50	71.42	76.15	79.49
60	35.53	37.48	40.48	43.19	46.46	59.33	74.40	79.08	83.30	88.38	91.95
70	43.28	45.44	48.76	51.74	55.33	69.33	85.53	90.53	95.02	100.42	104.22
80	51.17	53.54	57.15	60.39	64.28	79.33	96.58	101.88	106.63	112.33	116.32
90	59.20	61.75	65.65	69.13	73.29	89.33	107.57	113.14	118.14	124.12	128.30
100	67.33	70.06	74.22	77.93	82.36	99.33	118.50	124.34	129.56	135.81	140.17

ν = degrees of freedom.

國立雲林科技大學
98 學年度博士班招生考試試題

所別：工程科技研究所
科目：計算機演算法

1.For the sequence 18, 6, 23, 17, 10, 3, 8, 14, show the merge sort step by step recursively (25%).

2.Consider the following instance of the knapsack problem: n=3, M=20, (p1, p2, p3)=(25, 24, 15) and (w1, w2, w3)=(18, 15, 10). Please find the maximum profit (25%).

3. Given n numbers, use prune-and-search strategy to find its n/2 smallest element. (10%)

4. (40%)
(a)Describe the definitions of NP, P and NP-Completeness. (9%)
(b)Describe the concept of the Cook theorem. (6%)
(c)List the steps to prove a problem is NP-Completeness.(5%)
(d)Show that the partition problem is NP-Complete. Hint: The Sum of Subsets problem is a well-known NP-Complete problem. (20%)

國立雲林科技大學
98 學年度博士班招生考試試題

所別：工程科技研究所
科目：營建工程文獻評論

請閱讀本卷所附的文獻（共 9 頁），然後針對文獻內容回答下列各問題。

<u>選讀附件 1 者，依下列四點評論：</u>

(1) 本篇文獻之研究目的。(25 分)

(2) 本篇文獻之研究方法。(25 分)

(3) 本篇文獻之具體貢獻。(25 分)

(4) 本篇文獻之缺點與限制。(25 分)

ACI STRUCTURAL JOURNAL TECHNICAL PAPER

Title no. 106-S34

Behavior of Columns Constructed with Fibers and Self-Consolidating Concrete

by Hassan Aoude, William D. Cook, and Denis Mitchell

A series of 13 full-scale axial compression tests was conducted on reinforced concrete (RC) and steel fiber-reinforced concrete (SFRC) columns. The specimens, which were detailed with varying amounts of transverse reinforcement, were cast using self-consolidating concrete (SCC) that contained various quantities of fibers. The results demonstrate that the addition of fibers leads to improved load-carrying capacity and post-peak response. Furthermore, the addition of fibers greatly delays cover spalling. The results also show that the addition of steel fibers can partially substitute for the confinement reinforcement in columns, thereby improving constructibility while achieving significant confinement.

Keywords: bar buckling; columns; confinement; cover spalling; ductility; self-consolidating concrete; steel fibers.

INTRODUCTION

Steel fiber-reinforced concrete (SFRC) is a composite material whose components include the traditional constituents of portland cement concrete (hydraulic cement, fine and coarse aggregates, and admixtures) and a dispersion of randomly oriented short discrete steel fibers.[1]

The development of SFRC began in the early 1960s[2] when researchers first studied the concept of using steel fibers to improve the properties of conerete.[3,4] Since then, the use of SFRC has gathered great interest, with research demonstrating the potential benefits that may lie in the use of the material in both structural and nonstructural applications.[5-7] Several researchers have shown that steel fibers can improve many of the properties of reinforced concrete (RC) including shear resistance, ductility, and crack control.[8-10] The improved performance results from the ability of the randomly oriented fibers to arrest cracks and the resulting improvements in the post-cracking resistance of the concrete. In addition, some research has been carried out on the potential of using steel fibers in combination with traditional steel reinforcement.[11-13]

In high seismic risk regions, to improve confinement, closely spaced hoops often result in highly congested columns that may cause problems during construction. The use of SFRC in such columns may permit a reduction in the amount of transverse reinforcement,[14] leading to improved constructibility.

RESEARCH SIGNIFICANCE

Although much research exists on the structural applications of SFRC, the potential of using this material in load-carrying structural elements has yet to gain wide acceptance. This experimental program has been undertaken to gain a better understanding of the performance enhancements that can be gained from the use of SFRC in columns. An additional objective was to examine if the provision of fibers would permit a reduction of confinement reinforcement, thus leading to improved constructibility.

One of the drawbacks associated with SFRC is that the addition of fibers to a traditional conerete matrix can eause problems in workability.[15] To solve this problem, a highly flowable self-consolidating concrete (SCC) was used to improve workability and facilitate placement.

DETAILS OF TESTS SPECIMENS

An experimental program was condueted to investigate the effect of SFRC on the response of members subjected to pure axial compression loading. Thirteen full-scale RC columns, with various ratios of confinement reinforcement and with various fiber contents, were constructed and tested. The columns had an overall height of 1200 mm (47.2 in.) and were 300 x 300 mm (11.8 x 11.8 in.) in cross section with a 30 mm (1.2 in.) elear cover.

The longitudinal reinforcement consisted of eigbt 15M reinforcing bars (d_b = 16 mm [0.63 in.] and A_s = 200 mm^2 [0.31 in.^{2}]), resulting in a vertical steel reinforcement ratio of 1.8%. The transverse reinforcement was provided by 10M hoops (d_b = 11.3 mm [0.45 in.] and A_s = 100 mm^2 [0.16 in.^{2}]), anchored with seismic hooks. The confinement details were selected using the provisions of the 2004 CSA A23.3-04 Standard.[16] In all cases, the chosen hoop spacing for the various specimens was extended over the full height of the column.

A-series

The A-series specimens were detailed in accordance with the confinement provisions in Clause 7 of the 2004 CSA standard, for columns having a ductility-related force modification factor R_d of 1.5 (conventional construction). The confinement details are shown in Table 1 and Fig. 1(a) and 2(a).

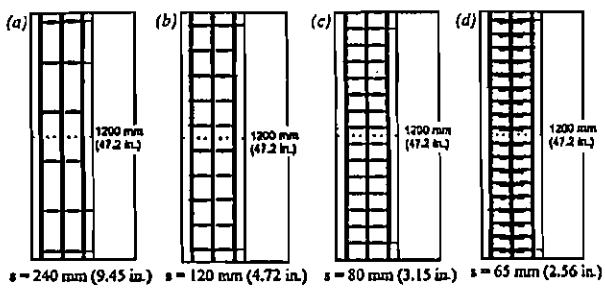


Fig. 1- Reinforcement details for: (a) A-series; (b) B-series; (c) D-series; and (d) C-series specimens.

ACI Structural Journal, V. 106, No. 3, May-June 2009.
MS No. S-2007-351.R1 received October 31, 2007, and reviewed under Institute publication policies. Pertinent discussion including author's closure, if any, will be published in the March-April 2010 *ACI Structural Journal* if the discussion is received by November 1, 2009.

Hassan Aoude *is a PhD Candidate in the Department of Civil Engineering and Applied Mechanics at McGill University, Montreal, QC, Canada. He received his BEng from McGill University and MEng. from Ecole de Technologie Supérieure, Montreal, QC, Canada. His research interests include the seismic behavior and design of reinforced concrete members and the structural use of fiber-reinforced and high-performance concretes.*

ACI member **William D. Cook** *is a Research Engineer in the Department of Civil Engineering and Applied Mechanics at McGill University. He received his PhD from McGill University. His research interests include behavior and design of regions near discontinuities in reinforced concrete members, nonlinear analysis of reinforced concrete structures, and the use of high-performance concrete.*

Denis Mitchell, *FACI, is a Professor in the Department of Civil Engineering and Applied Mechanics at McGill University. He is a member of ACI Committees 318, Structural Concrete Building Code; E803, Faculty Network Coordinating Committee; and Joint ACI-ASCE Committees 408, Development and Splicing of Deformed Bars; and 445, Shear and Torsion. His research interests include shear behavior and the use of high-performance concrete.*

The transverse reinforcement was provided by 10M hoops, having straight bar extensions of $6d_b$ for anchorage. The spacing s of the 10M hoops was governed by the bar buckling requirements of Clause 7.6.5.2, resulting in a required spacing of 240 mm (9.4 in.) ($16d_b$). This requirement is the same as the ACI Code[17] requirement (Section 7.10.5.2). Specimen A0 contained SCC concrete without any fibers. Specimens A1, A1.5, and A2 contained SCC concrete with steel fibers at volume ratios of 1%, 1.5%, and 2%, respectively.

B-series

The B-series specimens were detailed in accordance with the confinement provisions in Clause 21.7 of the CSA standard for columns having R_d of 2.5 (moderately ductile columns). The confinement details are shown in Table 1 and Fig. 1(b) and 2(a).

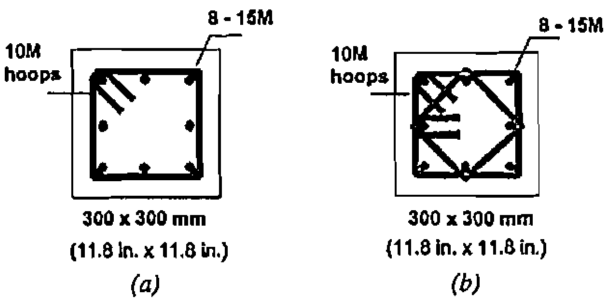


Fig. 2—Cross-sectional details for: (a) A-B-D series specimens; and (b) C-series specimens.

Table 1—Details of column specimens

Specimen	Cross section, mm (in.)	Fiber content, %	Confinement	Tie spacing, mm (in.)
A0	300 x 300 (11.8 x 11.8)	0	As per requirement of R_D = 1.5 of CSA	240 (9.45)
A1		1		
A1.5		1.5		
A2		2.0		
B0		0.0	As per requirement of R_D = 2.5 of CSA	120 (4.72)
B1		1.0		
B1.5		1.5		
B2		2.0		
C0		0.0	As per requirement of R_D = 4.0 of CSA	65 (2.56)
C1		1.0		
C1.5		1.5		
D0		0.0	Between R_D = 2.5 and 4.0	80 (3.15)
D1.5		1.5		

The spacing s of the 10M hoops was governed by the bar buckling requirements of Clause 21.7.2.2.3, resulting in a required spacing of 120 mm (4.7 in.) ($8d_b$). Specimen B0 was constructed without any fibers. Specimens B1, B1.5, and B2 contained SCC concrete with steel fibers having 1%, 1.5%, and 2% by volume, respectively.

C-series

The C-series specimens were detailed in accordance with the more stringent confinement provisions for ductile columns of Clause 21.4 in the CSA standard (R_d = 4.0). The confinement details are shown in Table 1 and Fig. 1(d) and 2(b).

Square- and diamond-shaped 10M hoops with seismic hooks were provided to ensure lateral support of each longitudinal bar, resulting in an effective area of confinement reinforcement of 341 mm^2 (0.53 in.^{2}) in each principal direction. Clause 21.4.4.3 of the CSA standard is intended to provide a minimum degree of confinement of the core and also to provide lateral support for the longitudinal bars. Clause 21.4.4.2 of the CSA standard takes into account the effects of axial loading, reinforcement arrangement, member dimensions, cross-sectional area of transverse reinforcement, and material properties of the concrete and the transverse steel.[18] These provisions resulted in a maximum hoop spacing s of 65 mm (2.6 in.). Specimen C0 contained SCC concrete without any fibers. Specimens C1 and C1.5 contained SCC concrete with steel fibers having 1% and 1.5% by volume, respectively.

D-series

The D-series specimens were detailed with a level of transverse reinforcement that is intermediate between the requirements for R_d = 2.5 and 4.0 of the CSA standard. The confinement details are shown in Table 1 and Fig. 1(e) and 2(a).

The transverse reinforcement was provided by 10M hoops at a spacing of 80 mm (3.2 in.). Specimen D0 contained SCC concrete without any fibers. Specimen D1.5 contained SCC concrete with steel fibers in a quantity of 1.5% by volume.

Materials

Steel fibers—Hooked-end steel fibers were used to attain 1% (76.8 kg/m^3 [4.9 lb/ft^3]), 1.5% (115.2 kg/m^3 [7.2 lb/ft^3]), and 2% fiber reinforcement (153.6 kg/m^3 [9.6 lb/ft^3]) by volume of concrete. The fibers were made from cold-drawn steel wire and are deformed with hooked ends. The 0.55 mm (0.02 in.) diameter fibers had a length of 30 mm (1.2 in.) resulting in an aspect-ratio (l/d) of 55. The tensile strength of the fibers was 1100 N/mm^2 (160 ksi).

Concrete—The concrete used in the various specimens consisted of a prepackaged SCC mixture. Table 2 lists the various SCC properties as specified by the manufacturer. The mixture contained a maximum aggregate size of 10 mm (0.4 in.) with a sand-to-aggregate ratio of approximately 0.45 and a water-cement ratio (w/c) of 0.42 was used. Furthermore, the SCC product contained an air-entraining admixture, a high-range water-reducing admixture, and a viscosity-modifying admixture (VMA), which were incorporated into the mixture in the form of dry powder.

Two batches of concrete (two casts) were used to produce the 13 reinforced concrete columns. Cast-1 was used to produce the concrete for Columns A0-B0-C0, A1.5-B1.5-C1.5, and A2-B2. A second cast (Cast-2) was used for Columns A1-B1-C1 and D0-D1.5. The compressive strengths f'_{co} were determined at the time of testing the columns by testing 100 mm (4 in.) diameter by 200 mm (8 in.) cylinders. The modulus of rupture f_r was determined from flexural beams that were tested in accordance with the ASTM C1018 test method.[19] Table 3 summarizes the concrete properties. It is noted that the concrete supplied by the manufacturer in Cast-2 had lower compressive cylinder strengths than that in Cast-1, due to a change in the manufacturing process. Figure 3 shows typical compressive stress-strain relationships for the concrete produced in both casts. As can be seen in Fig. 3, the addition of steel fibers has improved the descending branch of the compressive stress-strain responses. Figure 4 shows typical load-deflection responses obtained from the flexural beam tests. As expected, the plain concrete specimens have no ductility with a brittle failure occurring when the first crack forms. The addition of steel fibers, however, has transformed the brittle response of the plain concrete specimen by providing some significant post-cracking resistance, as seen in the descending branch of the load-deflection curves.

Steel reinforcement—The properties of the reinforcing steel are summarized in Table 4. Tension tests were performed on three random specimens for each bar size. The longitudinal reinforcement had average yield strengths f_y of 515 MPa (75 ksi), whereas the transverse reinforcement had an average yield strength of 409 MPa (60 ksi).

Workability of steel fiber-reinforced SCC

The L-box, slump-flow, and V-funnel tests were used to examine the influence of the fibers on the workability and flow characteristics of the SCC.[15] Tables 5 to 7 summarize the average results for the workability. As expected, the fibers reduced the workability of the SCC. The results from the slump-flow and V-funnel tests indicate that the 1.5%

Table 2—Concrete mixture proportions

Characteristics*	Content
HSF cement, kg/m³ (lb/ft³)	500 (31.2)
Mass density, kg/m³ (lb/ft³)	2300 (143.5)
Coarse aggregate, kg/m³ (lb/ft³)	765 (47.7)
Fine aggregate, kg/m³ (lb/ft³)	915 (57.1)
Ratio fine/total aggregates	0.45
w/c	0.42
Air content, %	7

*Details of manufacturer's additives are proprietary.

Table 3—Concrete properties

Series	Fiber content, %	Compressive strength f'_{co}, MPa (ksi)	Peak strain ε'_{co}	Modulus of rupture f_r, MPa (ksi)
Cast-1	0.0	49.5 (7.2)	0.0022	8.5 (1.2)
	1.5	47.6 (6.9)	0.0023	10.2 (1.5)
	2.0	45.9 (6.7)	0.0020	8.8 (1.3)
Cast-2	0.0	43.5 (6.3)	0.0021	7.7 (1.2)
	1.0	42.6 (6.2)	0.0021	8.0 (1.2)
	1.5	42.5 (6.2)	0.0021	8.5 (1.3)

Table 4—Reinforcing steel properties

Reinforcing bar	Yield stress f_y, MPa (ksi)	Strain at hardening ε_{sh}	Ultimate stress f_u, MPa (ksi)	Ultimate strain ε_u
10M	409 (60)	0.0095	640 (94)	0.174
15M	515 (75)	0.0194	625 (91)	0.165

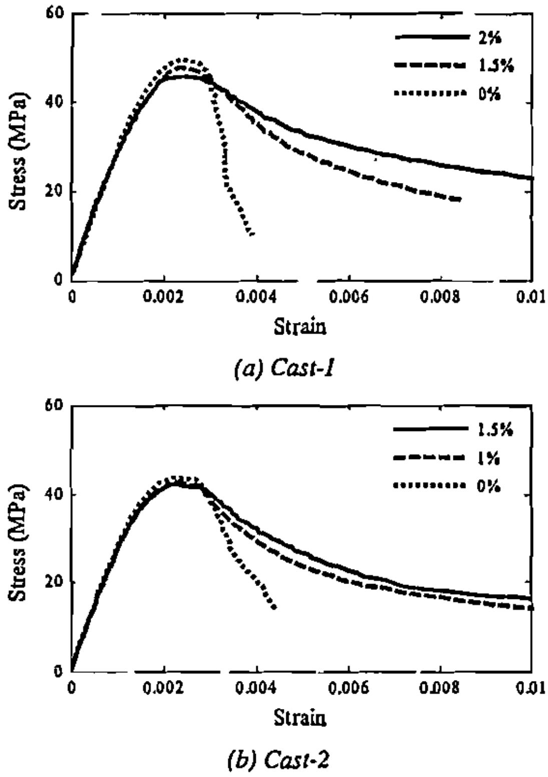


Fig. 3—Compressive stress-strain curves. (Note: 1 MPa = 0.145 ksi.)

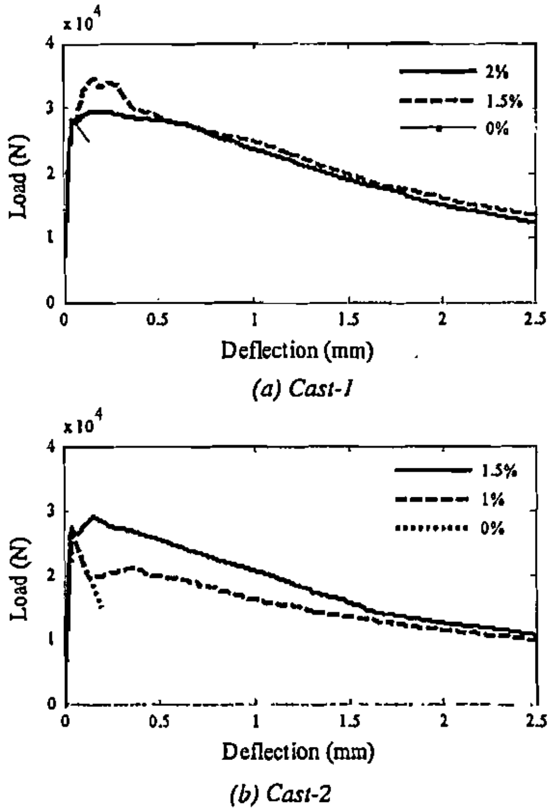


Fig. 4—Flexural load-deflection curves. (Note: 1 N = 0.000225 kips; 1 mm = 0.039 in.)

fiber content is an upper limit for a semi-workable mixture (refer to Tables 5 and 6). In addition, the results of the V-funnel test suggest that the 2% fiber content is too high for this type of SCC mixture (refer to Table 6). Also it is noted that the standard L-box test for SCC was not an adequate testing method for SCC containing steel fibers (refer to Table 7). It is suggested that this test method should be modified such that the bar size and the spacing between the bars matches the column reinforcement details.

During the actual casting of the columns, it was found that the 1% mixture was sufficiently workable, requiring no vibration, whereas the 1.5% mixture required some minimal vibration with a small 25 mm (1 in.) vibrator. On the other hand, the 2% mixture required significant vibration during placement and it was noted that a certain amount of segregation had taken place at this high fiber content.

TESTING OF SPECIMENS

Figure 5 shows some of the typical reinforcing cages before casting. The cages for the A-series specimens were relatively easy to construct, whereas those for the C-series specimens required significantly more effort and time to construct due to the congested reinforcement.

All of the column specimens were cast vertically. After casting the concrete, the specimens were moist cured using wet burlap and plastic sheets for a period of 5 days, after which the formwork was stripped. For the first series of experiments, the first specimen was tested at 38 days, whereas the last specimen was tested at 48 days.

All the specimens were tested under pure axial loading using an 11,400 kN (2600 kip) capacity MTS testing machine (refer to Fig. 6). Steel collars were placed at the top and bottom of each specimen to provide additional confinement in the end regions. All specimens were tested with a loading rate of 2.5 kN/s (0.562 kip/s) up to a load of 3000 kN (674 kip) and then displacement control was used at a rate of 0.002 mm/s (7.9×10^{-5} in./s). The tests then continued until the resistance of the given specimen dropped to 35% of the peak axial load or when the axial displacement reached a value of 30 mm (1.2 in.). The internal load cell of the MTS testing machine was used to measure the axial loads that were applied to the column specimens.

Four linear voltage differential transducers (LVDTs) were used to measure the axial deformations of each specimen under applied load and were placed vertically at the corners of each column over a length of 970 mm (38.2 in.).

Electrical resistance strain gauges were used to measure the strains in the steel reinforcement. For each column, a corner bar and a midside bar were instrumented at midheight of the column. Each instrumented longitudinal bar had a pair of strain gauges, with one gauge on the outside of the bar and the other on the inside of the bar, in an attempt to capture the onset of bar buckling. The instrumented hoops were located directly above the midheight of the specimens.

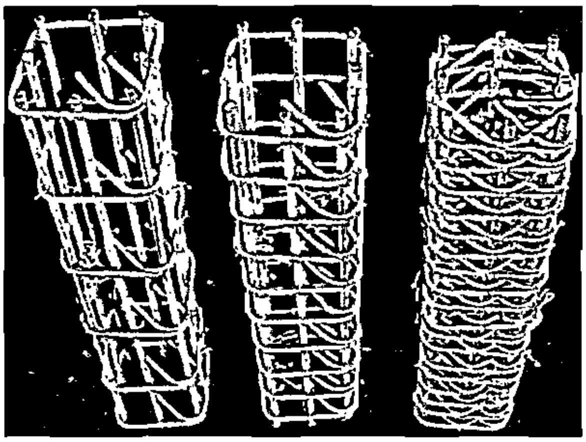


Fig. 5—Typical reinforcing cages prior to casting.

Fig. 6—Axially loaded specimen prior to testing.

EXPERIMENTAL RESULTS

To account for the different concrete strengths in Cast-1 and Cast-2, the normalized load-strain responses are used to compare the responses of the 13 columns. The normalized load P_n is computed as

$$P_n = \frac{P_c}{0.85 f'_{co} A_{net}} \quad (1)$$

where P_c is the axial load carried by the concrete; f'_{co} is the compressive strength of concrete; and A_{net} is the net cross-sectional concrete area.

Table 5—Results from slump flow test

Slump flow test				
Fiber content volume ratio, %	0.0	1.0	1.5	2.0
Slump height, mm (in.)	290 (11.4)	270 (10.6)	250 (9.8)	210 (8.3)
Slump diameter, mm (in.)	690 (27.1)	585 (23.0)	500 (19.7)	360 (14.2)

Table 6—Results from V-funnel test

V-funnel test				
Fiber content volume ratio, %	0.0	1.0	1.5	2.0
Flow time, seconds	2.7	3.9	11.9	Unsuccessful: no recorded flow time

Table 7—Results from L-box test

L-box test				
Fiber content volume ratio, %	0.0	1.0	1.5	2.0
Flow time, seconds	3.0	Unsuccessful (failure of test)		

The axial load carried by the concrete, P_c, is obtained by subtracting the force in the longitudinal bars from the total load. The steel force is determined at each load level by determining the stresses and forces in the longitudinal bars from the measured longitudinal strains. In the normalized load-strain curves, the strain corresponds to the average of the deformations measured by the four LVDTs in the central 970 mm (38.2 in.) region of each specimen.

Summary of peak loads

Table 8 summarizes the influence of confinement and the influence of fibers on the capacities. Table 8 gives the peak load P_{total}, the peak concrete contribution P_c, and the normalized concrete contribution P_n for each column. To allow for a comparison of the capacities from the two different concrete batches, the P_n values are compared.

For the specimens without fibers, as the degree of confinement increases, P_n increases with values of 0.99, 1.06, and 1.15 for Columns A0, B0, and C0, respectively. The influence of fibers on the concrete contribution is demonstrated by comparing the values of P_n within each of the series, A, B, C, and D. For example, the B series shows increases in P_n from 1.06 for Column B0 to 1.14 and 1.43 for Columns B1 and B1.5, respectively. This table shows the beneficial effects of increasing both the degree of confinement and the amount of fibers on the capability of the concrete to carry compression.

Load-versus-strain responses

A-series specimens—The A-series specimens were detailed in accordance with the basic confinement provisions of the CSA standard (R_d = 1.5) resulting in a tie spacing s of 240 mm (9.45 in.). The various columns contained a varying amount of fiber reinforcement. A comparison of the normalized load-strain responses for the four columns is shown in Fig. 7(a).

Specimen A0 had very little confinement due to the large spacing of the transverse reinforcement and, therefore, this column showed a sudden loss in load-carrying capacity after the peak resistance was reached. Specimen A1, which was detailed with the same amount of transverse reinforcement but contained 1% steel fibers, showed an increased normalized peak axial resistance as well as an improved post-peak response. These enhancements can be attributed to the improvement of the confinement and the delay of cover spalling due to the presence of the fibers. Similar conclusions can be made upon examining the response of Specimen A1.5, which had a fiber content of 1.5%.

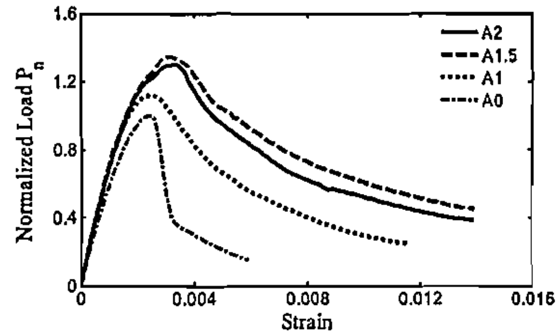
Table 8—Peak load-carrying capacities of various specimens

Specimen	Peak load P_{total}, kN (kip)	Peak concrete contribution P_c, kN (kip)	Normalized concrete contribution P_n
A0	4510 (1013)	3701(832)	0.995
A1	4471 (1005)	3671 (825)	1.147
A1.5	5783 (1300)	5008 (1126)	1.400
B0	4762 (1070)	3957 (890)	1.064
B1	4461 (1003)	3655 (821)	1.142
B1.5	5891 (1324)	5095 (1145)	1.425
C0	5044 (1134)	4288 (964)	1.153
C1	4650 (1045)	3827 (860)	1.196
C1.5	6209 (1396)	5394 (1213)	1.508
D0	4526 (1017)	3743 (841)	1.145
D1.5	5215 (1172)	4391 (987)	1.375

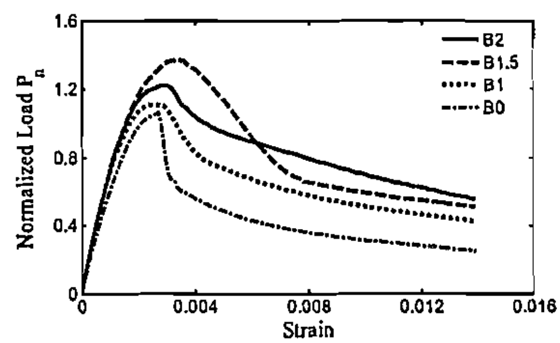
It is noted that the response of Specimen A2, which contained 2% fibers by volume, was not better than the response of the specimen constructed with a fiber content of 1.5% (as seen in Fig. 7(a)). This reduced fiber efficiency may have been the result of segregation during the necessary vibration of the concrete and due to clumping of the fibers.

B-series specimens—These columns had an intermediate amount of confinement reinforcement (R_d of 2.5; s = 120 mm [4.73 in.]) and varying amounts of fibers ranging from 0 to 2%. A comparison of the normalized load-strain responses for the four columns is shown in Fig. 7(b).

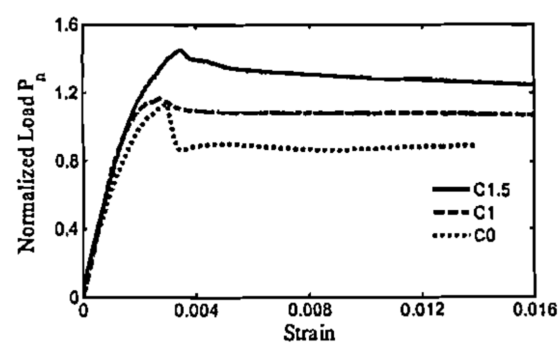
The tests conducted on the B-series specimens once again demonstrate that the addition of fibers greatly improves the performance of the columns when compared to the specimen without fibers. An increase in normalized peak axial resistance was observed in the fiber-reinforced specimens (refer to Specimens B1 and B1.5). Furthermore, the columns containing fibers demonstrated improved post-peak response,



(a) A-series specimens



(b) B-series specimens



(c) C-series specimens

Fig. 7—Normalized load-strain responses.

with the ability to maintain a higher post-peak load capacity with increasing strain.

The response of Specimen B2, which had a fiber content of 2%, had a lower peak load compared to the specimen containing 1.5% fibers. This result demonstrates the reduction in fiber efficiency at this higher fiber content.

C-series specimens—Specimens C0, C1, and C1.5 were detailed in accordance with the more stringent confinement provisions of the CSA standard (R_d of 4.0; s = 65 mm [2.56 in.]). The various columns contained a varying amount of fiber reinforcement ranging from 0 to 1.5%.

A comparison of the normalized load-strain responses for the three columns is shown in Fig. 7(c). An increase in the normalized peak axial resistance was observed in Specimen C1.5. This improvement was not as significant in Specimen C1.

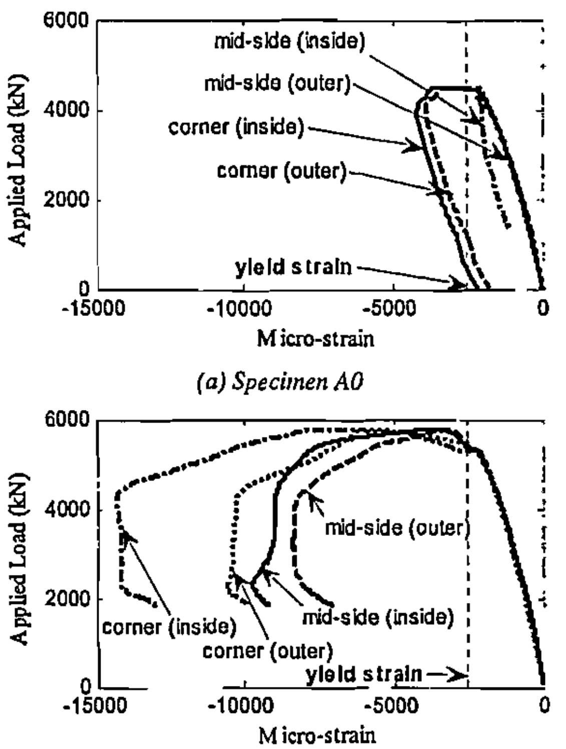
In terms of post-peak behavior, Specimen C0 had an exceptionally well-controlled response with the only drop in capacity occurring after cover spalling. This can be attributed to the excellent detailing and degree of confinement. The columns containing fibers displayed remarkably well-controlled post-peak behavior. The observed enhancements in performance could be attributed to the influence of the fibers in delaying and minimizing the effects of cover spalling and, to a lesser degree, to the improved confinement.

Load-versus-strain measurements in reinforcement

Strains measured on the vertical reinforcing bars in Specimen A0 are shown in Fig. 8(a). The load-versus-strain responses show that the yield strain was reached in the instrumented corner bar. Although the corner bar yielded, it did not reach very large strains due to the large spacing of the hoops. The gauges that were placed on the midside longitudinal reinforcing bar show that yielding was not reached due to the absence of lateral restraint (refer to Fig. 2(a)) and premature buckling.

The measured strain response of Specimen A1.5 is shown in Fig. 8(b). The measured strains from the gauges placed on the longitudinal reinforcement demonstrate that the yield strain was reached in the corner and midside bars. The plots also show that much larger compressive strains were reached in the longitudinal reinforcement of this column before the drop in load-carrying capacity when compared to Specimen A0. It is interesting to note that both the corner bar and the midside bar experienced larger compressive strains on the inside faces of the bars than on the outside faces after the peak load. This provides evidence that these bars were buckling outward.

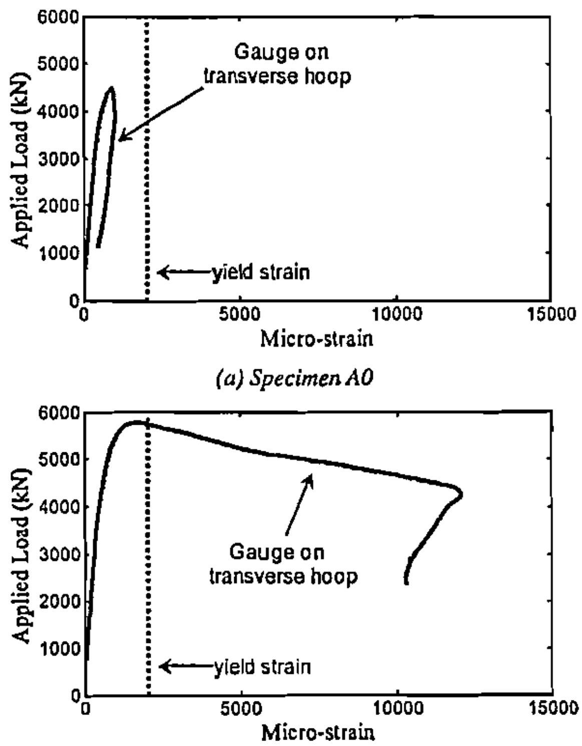
Figure 9(a) shows the measured strains in the instrumented hoop near the midheight of Specimen A0. The gauge readings show that the hoop at this location did not reach yield before failure in this poorly confined column. Figure 9(b) shows the measured strains in the instrumented hoop near the midheight of Specimen A1.5. The gauge shows that the yield strain was reached in the transverse hoop. It is noted that large tensile strains were measured as the column experienced the gradual decrease in load-carrying capacity. These results demonstrate that the steel fibers were able to improve the confinement of this column, which led to higher strains in the transverse reinforcement and an improved response. Similar observations were made when examining the responses of the other fiber-reinforced specimens.



(a) Specimen A0

(b) Specimen A1.5

Fig. 8—Measured strains in midside and corner bars at inside and outer gauge locations. (Note: 1 kN = 0.2248 kips.)



(a) Specimen A0

(b) Specimen A1.5

Fig. 9—Measured strains in transverse hoop. (Note: 1 kN = 0.2248 kips.)

Ability of fibers to substitute for confinement reinforcement

Specimens A1.5, A1 versus Specimen B0—A comparison of the normalized responses of Specimens A1.5 and B0 is shown in Fig. 10(a). It is noted that Specimen B0 had a two-fold increase in the amount of transverse reinforcement when compared to the A-series columns. This response comparison demonstrates that the addition of steel fibers in a column with minimum confinement reinforcement resulted in a column that had a level of performance that surpasses that of Specimen B0. In addition, Specimen A1, which contained 1% fibers by volume, showed a response that equaled or surpassed that of Specimen B0.

Specimens A1.5, A1 versus Specimen D0—A comparison of the normalized responses of Specimens A1.5 and D0 is shown in Fig. 10(b). Specimen D0 had a three-fold increase in the amount of transverse reinforcement when compared to Specimen A1.5. The response of Specimen A1.5 shows that this column was able to dissipate an amount of energy that was comparable to that of the specimen containing three times the amount of transverse reinforcement.

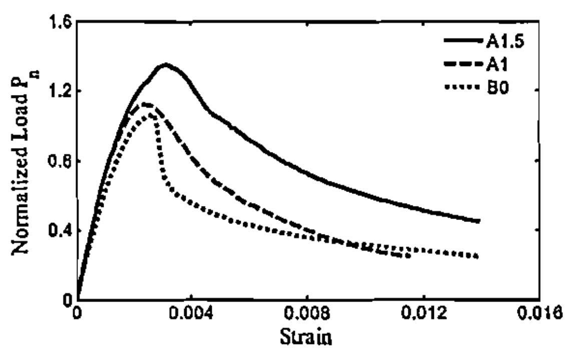
Specimens B1.5, B1 versus Specimen D0—A comparison of the experimental results of Specimens B1.5, B1, and D0 is shown in Fig. 11(a). Although D0 contained 1.5 times the amount of confinement reinforcement found in Specimens B1 and B1.5, the fiber-reinforced specimens showed higher peak loads and improved post-peak responses.

Specimen D1.5 versus Specimen C0—A comparison of the normalized load-strain responses of Specimen D1.5 and C0 is shown in Fig. 11(b). Specimen D1.5 had a tie spacing of 80 mm (4.7 in.). This column was able to maintain a higher normalized load than that of Specimen C0 (R_d = 4.0) up to a strain of 0.01 (after which its capacity dropped below that of Specimen C0, which continued to maintain its strength even at very high strains). This comparison shows that fibers can substitute for confinement reinforcement up to a certain point when compared to columns with ductile detailing.

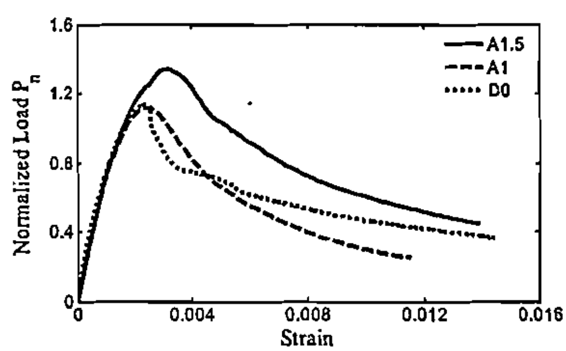
Effects of fibers on cover spalling and bar buckling

Sudden cover spalling was observed in all the specimens that were constructed without fibers. For example, crushing was observed in Specimen B0 (Fig. 12) near the midheight of the column soon after the peak load was reached. Similar observations were made for Specimens A0, C0, and D0.

This experimental program confirms observations made by Foster[20] that cover spalling is delayed due to the presence

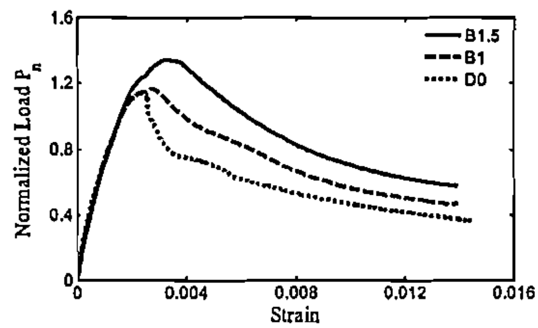


(a) Specimens A1.5, A1 versus Specimen B0

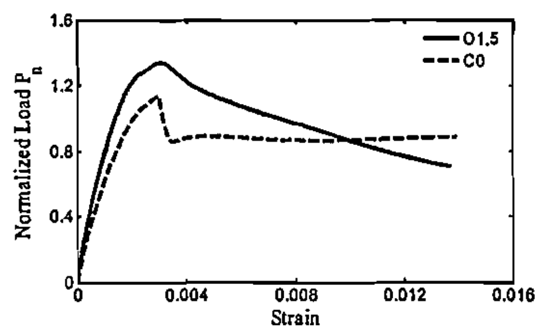


(b) Specimen A1.5, A1 versus Specimen D0

Fig. 10—Normalized load-strain responses.

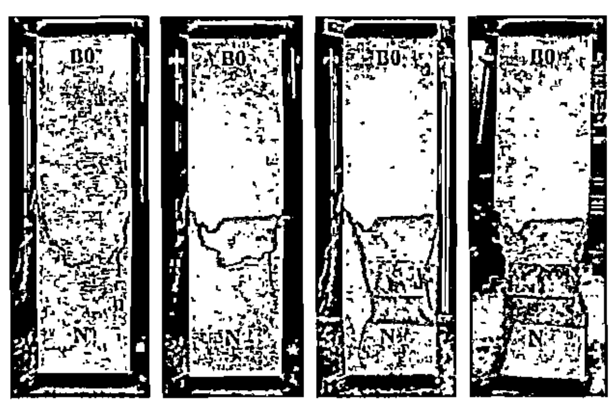


(a) Specimen B1.5, B1 versus Specimen D0



(b) Specimen D1.5 versus Specimen C0

Fig. 11—Normalized load-strain responses.



(a) *(b)* *(c)* *(d)*

Fig. 12—Sudden cover spalling in Specimen B0: (a) cracking just prior to peak load; (b) crushing after peak load reached; (c) sudden cover spalling; and (d) specimen at end of testing.

Fig. 13—Gradual cover spalling in Specimen B1.5: (a) cracking just prior to peak load; (b) controlled crushing; (c) gradual spalling of cover; and (d) specimen at end of testing.

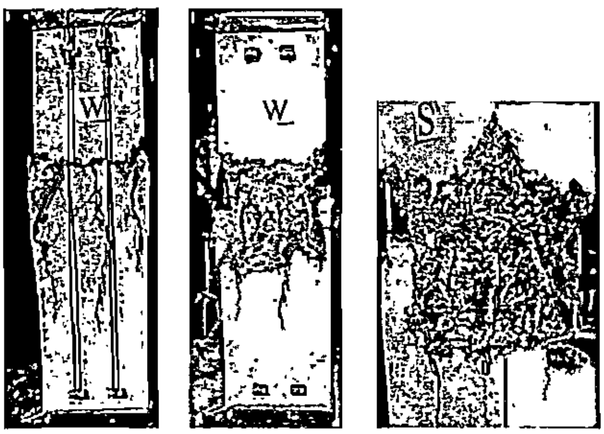


Fig. 14—Bar buckling in Specimen A1: (a) bars pushing against large pieces of cover; (b) specimen at end of testing; and (c) bar buckling.

of fibers. This enhancement is due to the ability of the fibers to limit the progression of cracks in the concrete, thereby resulting in greater material integrity at large strains. For example, Fig. 13 shows the stages in cover spalling in Specimen B1.5. It can be seen that, with the addition of the fibers, cover spalling was gradual and controlled.

Observations made during testing, however, demonstrated that although the cover did not spall, the longitudinal bars buckled. It was observed that the buckling bars pushed against the SFRC cover that was still carrying load but was partially detached from the core. Figure 14 shows a picture of the observed bar buckling in Specimen A1. This detachment was observed to occur more rapidly in the specimens with a larger spacing of transverse reinforcement (such as the A-series specimens).

SUMMARY AND CONCLUSIONS

Thirteen specimens constructed using plain and fiber-reinforced concrete and containing varying amounts of transverse reinforcement were tested under pure axial compression loading. These tests examined the influence of several parameters, including the effect of fibers on confinement, cover spalling, and bar buckling. In addition, SCC was used in an attempt to improve the workability of the SFRC. From this series of tests, the following conclusions can be made:

1. An addition of moderate amounts of fibers to SCC can result in an adequately workable concrete mixture. There is a limiting fiber content (1.5% in this test program), however, above which the SCC mixture can lose much of its workability, leading to reduced fiber efficiency;
2. The addition of steel fibers in reinforced concrete columns can lead to improvements, including an increase in peak load-carrying capacity of the column and a significant improvement in the post-peak response of the column;
3. The results showed that steel fibers, up to approximately 1.5% by volume, can partially substitute for the transverse reinforcement in RC columns and hence could result in improved constructibility; and
4. It was observed that fibers transform the cover spalling from a sudden mechanism to a gradual mechanism. The addition of fibers, however, did not prevent bar buckling from occurring.

ACKNOWLEDGMENTS

This research program was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Fonds Quebecois de la Recherche sur la Nature et les Technologies (FQRNT). The authors wish to express their gratitude to Bekaert Steel Wire Co. for the donation of the fibers.

NOTATION

A_{net} = net cross-sectional concrete area
A_s = cross-sectional area of steel reinforcement
d_b = diameter of steel reinforcement
f'_{co} = compressive strength of concrete
f_r = modulus of rupture of concrete
f_u = ultimate stress of steel reinforcement
f_y = yield stress of steel reinforcement
P_c = axial load carried by concrete
P_n = normalized axial load
P_{total} = total applied axial load
R_d = ductility-related force modification factor
ε'_{co} = peak strain of concrete
ε_{sh} = strain at hardening of steel reinforcement
ε_u = ultimate strain of steel reinforcement

REFERENCES

1. Johnston, C., *Fiber-Reinforced Cements and Concretes, Advances in Concrete Technology*, Gordon & Breach, the Netherlands, 2001, 372 pp.
2. Li, V. C., "Large Volume, High-Performance Applications of Fibers in Civil Engineering," *Journal of Applied Polymer Science*, V. 83, No. 3, 2002, pp. 660-686.
3. Romuldi, J. P., and Baston, G. B., "Mechanics of Crack Arrest in Concrete," *Proceedings of the American Society of Civil Engineering*, V. 89, 1963, pp. 147-168.
4. Romuldi, J. P., and Mandel, J. A., "Tensile Strength of Concrete Affected by Uniformly Distributed Closely Spaced Short Lengths of Wire Reinforcement," ACI JOURNAL, *Proceedings* V. 61, No. 6, 1964, pp. 657-671.
5. Banthia, N., and Mindess, S., *Fiber Reinforced Concrete: Modern Developments*, University of British Columbia Press, Vancouver, BC, Canada, 1995, 417 pp.
6. Bentur, A., and Mindess, S., *Fiber Reinforced Cementitious Composites*, Elsevier Applied Science, UK, 1990, 470 pp.
7. Balagaru, P. N., and Shah, S. P., *Fiber Reinforced Cement Composites*, McGraw-Hill, New York, 1992, 530 pp.
8. Sharma, A. K., "Shear Strength of Steel Fiber-Reinforced Concrete Beams," ACI JOURNAL, *Proceedings* V. 83, No. 4, July-Aug. 1986, pp. 624-628.
9. Narayanan, R., and Darwish, I. Y. S., "Use of Steel Fibers as Shear Reinforcement," *ACI Structural Journal*, V. 84, No. 3, May-June 1987, pp. 216-227.
10. Abrishami, H. H., and Mitchell, D., "Influence of Steel Fibers on Tension Stiffening," *ACI Structural Journal*, V. 94, No. 6, Nov.-Dec. 1997, pp. 769-776.
11. Massicotte, B.; Mossor, B.; Filliatrault, A.; and Tremblay, S.,

"Compressive Strength and Ductility of Steel Fiber Reinforced Concrete Columns," *Structural Applications of Fiber-Reinforced Concrete*, SP-182, N. Banthia, C. MacDonald, and P. Tatnall, eds., American Concrete Institute, Farmington Hills, MI, 1998, pp. 163-180.

12. Foster, S. J., and Attard, M. M., "Strength and Ductility of Fiber-Reinforced High-Strength Concrete Columns," *Journal of Structural Engineering*, ASCE, V. 127, No. 1, 2001, pp. 28-34.

13. Minelli, F., *Plain and Fiber Reinforced Concrete Beams under Shear Loading: Structural Behavior and Design Aspects*, Starrylink Editrice, Brescia, 2005, 429 pp.

14. Campione, G., "The Effects of Fibers on the Confinement Models for Concrete Columns," *Canadian Journal of Civil Engineering*, V. 29, No. 5, 2002, pp. 742-750.

15. Khayat, K. H., and Roussel, Y., "Testing and Performance of Fiber-Reinforced, Self-Consolidating Concrete," *Materials and Structures*, V. 33, No. 230, 2000, pp. 391-397.

16. Canadian Standards Association, "Design of Concrete Structures (CSA A23.3-04)," Mississauga, ON, Canada, 2004, 358 pp.

17. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (318R-05)," American Concrete Institute, Farmington Hills, MI, 2005, 430 pp.

18. Mitchell, D., and Paultre, P., *CAC Concrete Design Handbook*, Chapter 11, Cement Association of Canada, Ottawa, ON, Canada, 2006, pp. 1-60.

19. ASTM C1018, "Standard Test Method for Flexural Toughness and First Crack Strength of Fiber-Reinforced Concrete," ASTM International, West Conshohocken, PA, 1998, 7 pp.

20. Foster, S. J., "On Behavior of High-Strength Concrete Columns: Cover Spalling, Steel Fibers, and Ductility," *ACI Structural Journal*, V. 98, No. 4, July-Aug. 2001, pp. 583-589.

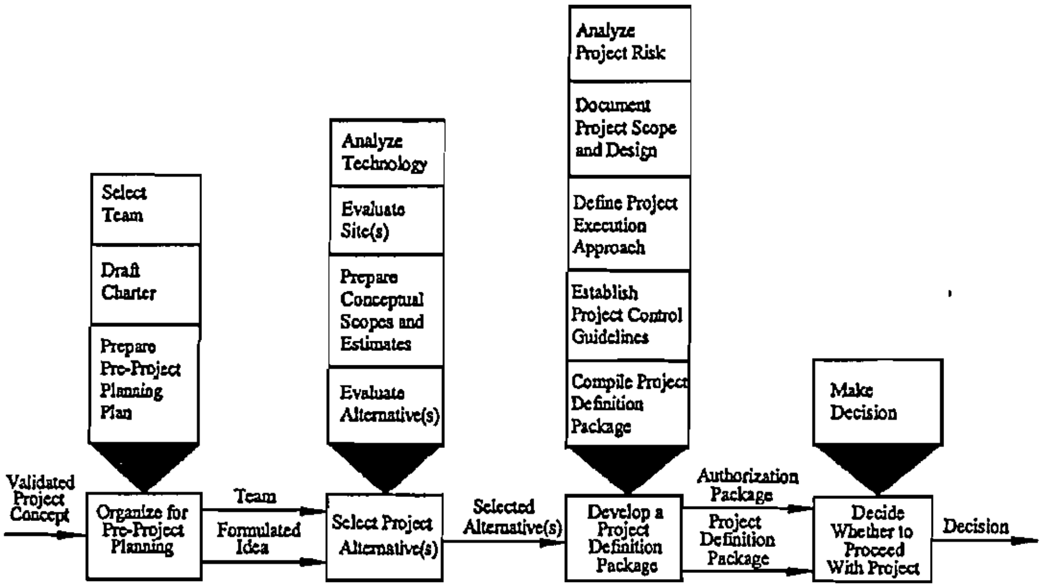


Fig. 1. Preproject planning process

operational characteristics (Hamilton and Gibson 1996; Dumont et al. 1997; Griffith et al. 1999; Cho et al. 1999). Success during the detailed design, construction, and startup phases of a project depends highly on the level of effort expended during the scope definition phase and the efficacy of the project scope definition package (Dumont et al. 1997; Cho et al. 1999). Although each of these research studies has focused on different owner organizations and/or project types, significant similarities exist in the preproject planning process. This article will address holistic findings of these studies as they apply to project management professionals. The following discussion summarizes these five preproject planning research studies, including a brief overview of the methodology and analysis techniques.

Study 1: Preproject Planning

In 1991, the Construction Industry Institute (CII) chartered a research project "to find the most effective methods of project definition and cost estimating for appropriation approval." A research team composed of 16 industry practitioners (nine from owner organizations and seven from contractor organizations) and two faculty members was constituted to investigate this issue. This team helped map the preproject planning process using the U.S. Air Force's Structured Analysis and Design Technique (Gibson et al. 1995). The effort included an analysis of 62 capital projects that were randomly selected from a nominated pool of industrial projects offered by 24 owner organizations. This data sample represented $3.4 billion in total project costs and included chemical, petrochemical, power, consumer products, petroleum refinery, and other manufacturing facilities. The research team used a detailed questionnaire to quantify practice use and performance outcomes on these projects and conducted 131 structured interviews and three project case studies (Hamilton and Gibson 1996; Griffith et al. 1999).

Preproject planning was defined in this first study as "the process of developing sufficient strategic information with which owners can address risk and decide to commit resources to maximize the chance for a successful project" (CII 1994). Other terms used in the industry for preproject planning include front-end loading, front-end planning, feasibility analysis, programming/schematic design, and conceptual planning. The research team developed a process map for preproject planning as given in Fig. 1. The preproject planning process can be summarized into four major steps: (1) organize for preproject planning; (2) select project alternative(s); (3) develop a project definition package (which is the detailed scope definition of the project); and (4) decide whether to proceed with detailed design of the project (Gibson et al. 1995).

Study 2: Front-End Planning

CII assembled another research team in 1994 in order to extend the previous research effort to allow owner and contractor companies to better achieve business, operational, and project objectives (Gibson and Dumont 1996b). This team consisted of 15 industry practitioners (eight from owner companies and seven from contractors) and the academic research team. The goal was to develop effective and easy-to-use preproject planning management tools. Two objectives were established in order to reach this goal: (1) quantify preproject planning efforts; and (2) analyze the impact of the alignment of the project participants on a common set of project goals.

This effort produced the Project Definition Rating Index for Industrial Projects (PDRI-Industrial) as a scope definition tool. The PDRI is a weighted matrix with 70 scope definition elements (issues that need to be addressed during preproject planning) grouped into 15 categories and further summarized into three main sections. Thirty-three pages of detailed descriptions define the 70 scope definition elements (Gibson and Dumont 1996a). The development effort for this tool included input from more than 70 individuals during three workshops, as well as the use of scope definition documents from 14 companies (Gibson and Dumont 1996b; Dumont et al. 1997). The team used input from 54 experienced project managers and estimators to weight

CATEGORY Element	Definition Level						Score
	0	1	2	3	4	5	
A. MANUFACTURING OBJECTIVES CRITERIA (Maximum Score = 45)							
A1. Reliability Philosophy	0	1	5	9	14	20	
A2. Maintenance Philosophy	0	1	3	5	7	9	
A3. Operating Philosophy	0	1	4	7	12	16	
CATEGORY A TOTAL							

Fig. 2. Example PDRI-Industrial score sheet for Category A

each element based on its relative impact on overall project performance.

Fig. 2 is an example of one of the 15 categories, "A. Manufacturing Objectives Criteria," which includes the weights for each of the elements. Fig. 3 is a representative example PDRI description for element "A1. Reliability Philosophy." When a project team uses the PDRI during preproject planning, it first reads the description of each element, assesses the definition level for each element based on the given description, and then takes actions to improve the scope definition of those elements that present the greatest risks (indicated by the highest weights) to the project.

The PDRI allows a project team to quantify the completeness of a project's scope definition. The maximum score is 1,000 points, and a lower score represents a more complete scope definition (Gibson and Dumont 1996b). The PDRI was initially validated as an effective scope definition tool using a sample of 40 industrial projects, representing approximately $3.3 billion (Dumont et al. 1997). An additional 22 projects were collected through CII's Benchmarking and Metrics program, resulting in a total of 62 industrial projects for this effort. Project performance and PDRI data were collected from the sample projects and showed that the PDRI score and project success were statistically related; that is, a low PDRI score (representing a better-defined project scope definition package just prior to detailed design) correlates to an increased probability for project success. Project success was quantified based on cost performance, schedule performance, percentage of design capacity (volume, yield, etc.) obtained at 6 months, and plant utilization attained at 6 months (Wang 2002).

This second research investigation also analyzed the degree to which the stated project goals supported the business needs of the organization and the degree to which the goals of the owner's business, project management, and operations personnel, as well as key contractor personnel, supported these stated project goals. The term *alignment* was used to describe "the condition where appropriate project participants are working within acceptable tolerances to develop and meet a uniformly defined and understood set of project objectives" (Griffith and Gibson 2001). This analysis was based on input from more than 100 industry participants

A1. Reliability Philosophy

A list of the general design principles to be considered to achieve dependable operating performance from the unit. Evaluation criteria should include:

- ☐ Justification of spare equipment
- ☐ Control, alarm, and safety systems redundancy
- ☐ Extent of providing surge and intermediate storage capacity to permit independent shutdown of portions of the plant
- ☐ Mechanical/structural integrity of components (metallurgy, seals, types of couplings, bearing selection, etc.)

Fig. 3. Example PDRI-Industrial element description

(representing 19 contractor and owner companies) collected through structured interviews and three workshops and an in-depth evaluation of 20 capital projects. Ten critical alignment issues were identified to have significant impact on project alignment and on the potential for project success. A linear regression analysis demonstrated that alignment was positively related to project success for this sample of 20 capital projects. The research results show that achieving and maintaining alignment is a key factor in preproject planning and in achieving project success (Griffith and Gibson 2001).

Study 3: Office of Facility Planning and Construction (OFPC)

The University of Texas (UT) System OFPC commissioned this study to address early project planning on University of Texas System capital projects. The objectives were: (1) to describe the performance of OFPC capital projects completed from 1990 to 1995 and use the results as a baseline for improvement; (2) to describe the extent of preproject planning performed on these projects; and (3) to provide recommendations for improving the early planning of UT System capital projects (Gibson et al. 1997).

Information from 37 building projects, representing approximately $402 million of total constructed cost, was collected. This sample, which included new, renovation, and engineering/specialty projects, was studied based on preproject planning practice use, as well as project performance in terms of cost, schedule, and contract modifications. Variables impacting schedule and cost changes were identified and analyzed.

This third study specifically investigated the relationship between the preproject planning effort expended and project performance metrics. Descriptive statistics, analysis of variance, *t*-tests and qualitative methods were used in the analysis. A facility programming guide process was developed to help improve future planning efforts, and the capital budgeting process for OFPC was modified to put more emphasis on scope definition. Some of the key conclusions from the research were that, for the sample projects, cost estimates and schedules submitted for approval were often poorly defined and unrealistic, and a lack of early requirements determination or scope definition between planners and project sponsors led to a number of design and construction changes initiated by end users during the execution phase.

Study 4a: PDRI-Buildings

The first PDRI (Study 2 above) was developed specifically to measure the completeness of industrial project scope definition and has been widely used as a planning tool by the industry. In response to requests from its members, CII commissioned a study in 1997 to develop a similar tool for building projects (Cho et al. 1999; Cho and Gibson 2001). This effort was chartered to develop a user-friendly and generic tool for measuring project scope definition for commercial and institutional buildings and then to validate the tool through testing on sample projects. A team consisting of 17 industry practitioners (eight from owner organizations and nine from contractors) provided guidance to the academic researchers.

This study led to the development of the Project Definition Rating Index for Building Projects (PDRI-Buildings). The PDRI-Buildings consists of 64 scope definition elements in a weighted checklist format, which are grouped into 11 categories and further

CATEGORY Element	Definition Level						Score
	0	1	2	3	4	5	
G. EQUIPMENT (Maximum Score = 36)							
G1. Equipment List	0	1	5	8	12	15	
G2. Equipment Location Drawings	0	1	3	5	8	10	
G3. Equipment Utility Requirements	0	1	4	6	9	11	
CATEGORY G TOTAL							

Definition Levels

0 = Not Applicable
1 = Complete Definition
2 = Minor Deficiencies
3 = Some Deficiencies
4 = Major Deficiencies
5 = Incomplete or Poor Definition

Fig. 4. Example PDRI-Buildings score sheet for Category G

summarized into three sections. It is very similar in format to the PDRI-Industrial. Thirty-seven pages of detailed descriptions define the 64 scope definition elements (Gibson 1999).

The development effort for this tool included seven workshops and input from more than 100 individuals, including engineers, architects, and other industry professionals directly involved in planning and executing building projects. The team used input from a broad range of construction industry experts in a series of industry-practitioner workshops to weight each element based on its relative impact on overall project performance. Higher weights were assigned to those elements whose lack of definition could have the most serious negative effect on project performance.

Fig. 4 is an example of one of the 11 categories, "G. Equipment," which includes the weights for each of the elements. Fig. 5 is a representative example PDRI description for element "G2. Equipment Location Drawings."

PDRI-Buildings was tested on completed projects to validate its viability as a predictor of project success (Cho and Gibson 2001). A data sample of 33 projects from 10 owner organizations was collected, and the relationship between PDRI scores and project performance was analyzed using regression analysis, analysis of variance, and qualitative assessments. PDRI-Buildings scores were computed for each project at a point in time just prior to development of construction documents and compared to completed project success criteria, such as cost and schedule performance (note that this was an after-the-fact evaluation, so the PDRI assessments were based on the project participants' memories of what was known at the time). Analysis results revealed a significant difference between projects with a lower PDRI score (better preproject planning efforts) and projects with higher PDRI scores in terms of cost, schedule, and change order performance.

Study 4b: PDRI Benchmarking Study

Since its introduction in 1999, the PDRI-Buildings has been widely used by industry practitioners and has proven to be an effective tool for scope definition of building sector capital projects. One institutional organization (which prefers to remain

G2. Equipment Location Drawings

Equipment location/arrangement drawings identify the specific location of each item of equipment in a project. These drawings should identify items such as:

- ☐ Plan and elevation views of equipment and platforms
- ☐ Location of equipment rooms
- ☐ Physical support requirement (e.g., installation bolt patterns)
- ☐ Coordinates or location of all major equipment

Fig. 5. Example PDRI-Buildings element description

Table 1. Preproject Planning Effort Summary

Research study	Year study completed	Number of projects	Represented cost (U.S. billion $)
Study 1: Preproject planning	1994	62	3.4
Study 2: Front end planning	2001	62	3.8
Study 3: OFPC	1997	37	0.4
Studies 4a and b: PDRI-Buildings and benchmarking	1999 and 2001	78	1.1
Total		239	8.7

anonymous) approached researchers at UT and expressed interest in deploying the PDRI for their large capital program. The objective of this effort was to slightly modify the PDRI-Buildings to reflect the needs of this organization's budgeting cycle, to develop an extensible benchmarking database, and to provide a path forward for implementation (Wang 2002).

A workshop was held to modify the PDRI-Buildings to reflect the organization's specific terminology. A detailed project questionnaire and a user survey were developed and sent to respective project managers and end users. Data from 45 building projects were collected and studied.

Conclusions and recommendations based on the data analysis were provided for the organization's future capital project development. For this sample, projects with more well-developed scope definition saw better performance in terms of cost, schedule, and change orders (Wang 2002). A lack of end user involvement (poor alignment) was a common problem (Wang 2002). In addition, a benchmarking database was developed for the organization. Taken together, the samples from Studies 4a and 4b represent approximately $1.1 billion in building-type projects analyzed using the PDRI-Buildings tool.

Table 1 summarizes the five major research studies. The sample projects are representative of two major industry sectors, industrial facilities and building projects (Wang 2002).

Findings

Findings from these research efforts are presented based on the collective knowledge gained by the writers from these studies. Several common themes have emerged. The following five points summarize the critical issues that must be addressed in order to adequately perform preproject planning on a capital facility. Similarities and differences of scope definition elements between building and industrial projects are also outlined:

1. *Preproject planning is a process that can positively impact capital project performance.*

A common understanding among many industry practitioners is that it is much easier to influence a project's outcome during the project planning stage, when expenditures are relatively minimal, than to affect the outcome during project execution or operation of the facility, when expenditures are much more significant (CII 1995). However, many organizations do not understand this fact and therefore do not place proper emphasis on preproject planning. The following results from selected samples illustrate this potential impact.

Two indices, a preproject planning index and a success index, were established from the sample projects in Study 1 to measure

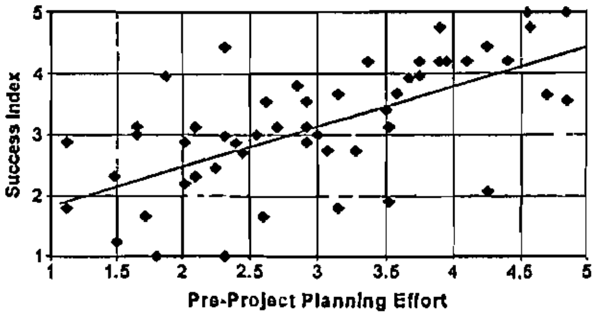


Fig. 6. Success index versus preproject planning effort index, $N=53$

preproject planning effort and project success. The preproject planning index was designed to measure the level of effort expended for preproject planning prior to formal authorization by the owner organization and consisted of six weighted variables (Hamilton and Gibson 1996). The index was established with a score ranging from 1 (the lowest level of preproject planning effort) to 5 (the highest level). The success index was designed to measure the outcomes of project execution and included a weighted blend of budget, schedule, design capacity, and utilization performance versus target. Again, the index had a scoring range of 1 (complete failure) to 5 (complete success). Fig. 6 shows the preproject planning effort and success index scores for the 53 projects surveyed. The regression equation resulted in a coefficient of determination, R^2, of 0.42 and a significance level of 0.01 (Hamilton and Gibson 1996).

In Study 2, a detailed evaluation of 62 industrial projects was conducted by measuring the 70 scope definition elements in the PDRI at the completion of scope development in relation to project performance parameters. Table 2 compares project performance for industrial projects exhibiting PDRI scores below and above 200 points. Projects with a PDRI score under 200 (more well-defined projects) statistically outperformed projects with a PDRI score above 200 (Wang 2002). The table shows the mean actual performance as compared to execution estimates. The cost and schedule performance are measured by comparing actual cost/schedule to budgeted cost/schedule at the beginning of detailed design. Change orders are measured by taking the absolute value of change orders as a percentage of the cost estimate at the beginning of detailed design.

A similar evaluation was performed on the sample of 78 building projects from Studies 4a and 4b. Table 3 summarizes the project performance and PDRI scores for these building projects. Again, projects with better scope definition (lower PDRI score) significantly outperformed projects with poor scope definition (Wang 2002).

Table 2. Comparison of Projects with PDRI-Industrial Projects Score Above and Below 200 (Gibson and Pappas 2003)

	PDRI score	
Performance	<200	>200
Cost	3% below budget	9% above budget
Schedule	1% ahead of schedule	8% behind schedule
Change orders	6% of budget	8% of budget
	(N=35)	(N=27)

Table 3. Comparison of Projects with PDRI-Building Projects Score Above and Below 200 (Gibson and Pappas 2003)

	PDRI score	
Performance	<200	>200
Cost	3% below budget	13% above budget
Schedule	3% ahead of schedule	21% behind schedule
Change orders	7% of budget	14% of budget
	(N=17)	(N=61)

It should be noted that thorough scope definition during preproject planning impacts project results in three ways. First, it allows the project team to more accurately predict the cost and schedule for detailed design and construction. Second, the team can reduce the real cost of the project versus other similar projects, because scope alternatives are addressed earlier in the project. Finally, achieving alignment—involving stakeholders and obtaining their commitment—in the scope definition process typically results in fewer user-initiated changes during design and construction.

2. Preproject planning is a critical project process that must be performed consistently on each project.

The process for performing adequate preproject planning for capital facility projects is shown in Fig. 1. It involves: (1) organizing the planning effort and getting appropriate stakeholder representation; (2) selecting key alternatives, including site and technology selection; (3) developing a detailed, written scope of work, including risk analysis, control guidelines, execution approach, and scope documentation; and (4) measured and consistent decision making. This general process was developed based on studying those used by more than 100 organizations over the past 14 years (CII 1994; Gibson and Dumont 1996b; Gibson et al. 1997; Cho et al. 1999; Gibson and Pappas 2003). An organization's commitment, resources, and technical expertise applied to the process were the key differences observed in planning effectiveness. In general, most organizations with successful planning processes use a series of "gateway" checks to ensure the process is being performed adequately by the project team, and consistently across all projects, before the project moves to the next phase.

The recommendations from Study 3 to improve UT System's capital project performance provide a good example. They included: (1) standardizing the preproject planning process; (2) ensuring that proper technical expertise was involved during preproject planning; (3) performing adequate programming (space planning) on projects prior to schematic design; (4) ensuring adequate site investigations; and (5) including appropriate individuals (stakeholders) and end users in the programming, schematic design, and design development phases (Gibson et al. 1997). These changes were institutionalized within the organization's capital approval process and are monitored by the UT System's Board of Regents.

The federal government recently commissioned a study of the planning processes of 13 government agencies based on these principles, which led to recommendations to enhance the consistency and quality of preproject planning of federal facility projects (Gibson and Pappas 2003).

3. The project manager and team must ensure that it is performing the "right project."

It should be noted that many organizations plan and construct facilities that do not add value to their project portfolio. Good project objective setting, requirements determination using key

Table 4. Critical Scope Definition Elements To Determine the "Right Project"

Industrial projects	Building projects
Products	Building use
Capacities	Facility requirements
Technology	Site selection considerations
Processes	Business justification
Market strategy	Business plan
Project objectives	Future expansion/alteration considerations
Reliability philosophy	Evaluation of existing facilities

stakeholders, and team alignment are absolutely essential in the very early phases of the project. The team must address the expectations of the project sponsor, including the selection of major project alternatives such as location and technology content. In general, the identified project requirements should conform to and enhance the mission or business requirements of the sponsoring organization.

The process of achieving alignment is not easy. Study 2 identified 10 issues that impact alignment and correlate statistically to project success on the sample of industrial projects (Griffith and Gibson 2001). These issues can help the project team align its focus on project objectives and include: (1) appropriate stakeholder representation on the project team; (2) defined, effective, and accountable project leadership; (3) clear priorities between cost, schedule, and project features; (4) open and effective communication within the team and with stakeholders; (5) timely and productive team meetings; (6) trust, honesty, and shared values fostering team culture; (7) a preproject planning process that includes sufficient funding, schedule, and scope to meet objectives; (8) reward and recognition systems that promote meeting project objectives; (9) effective teamwork and use of team building techniques; and (10) effective use of planning tools.

Table 4 outlines the types of scope definition issues that need to be addressed and defined to ensure the organization pursues the right project. These issues were selected from the PDRI-Industrial and PDRI-Buildings, and each is described in detail in the respective PDRI publications (Gibson and Dumont 1996 and Gibson 1999). Note that most of these issues are related to the business opportunity, overall use, and operational focus of the facility.

4. The project manager and team must ensure that it is developing the "right work product" during preproject planning. After key alternatives have been selected and the team is aligned toward the correct business venture, it must identify, address, and document the right scope definition elements to ensure that the project has a good design basis in order to provide a smooth transition from preproject planning to design and construction (Wang 2002). In particular, the project team should perform and document a site evaluation; develop flow design documents (space planning for buildings or process flow diagrams for industrial facilities); document design parameters such as code, regulatory, standards, and user preferences; and identify detailed equipment requirements. Table 5 lists some of the issues that need to be defined prior to beginning detailed design. Again, these issues were selected from the PDRI-Industrial and PDRI-Buildings and are discussed in detail in those documents (Gibson and Dumont 1996b; Gibson 1999).

Table 5. Critical Scope Definition Elements To Determine the "Right Work Product"

Industrial projects	Building projects
Site location	Environmental assessment
Environmental assessment	Civil/geotechnical information
Plot plan	Architectural design parameters
Process flow sheets	Program statement
Process and instrumentation diagrams (P&IDs)	Building summary space list
Heat and material balances	Mechanical design parameters
Utility sources with supply conditions	Structural design parameters
Mechanical equipment list	Equipment list

Table 6. Critical Scope Definition Elements To Determine the "Right Approach" to Design and Construction Execution

Industrial projects	Building projects
Project schedule	Project schedule
Project cost estimate	Project cost estimate
Long-lead/critical equipment and materials	Long-lead/critical equipment and materials
Project control requirements	Risk management plan
Engineering/construction plan and approach	Project schedule control method
Procurement procedures and plans	Project delivery method
Shut down/turnaround requirements	Design/construction plan and approach
Startup requirements	Project cost control methods

5. The project manager and team must choose the "right approach" to project design and construction execution. Finally, the team must choose an appropriate execution approach to ensure a good basis for successfully managing the project during design and construction. Failure to properly address design and construction execution issues in preproject planning could severely impact the cost and schedule performance of the project. The project team should address baseline cost and schedule development, execution planning issues, the acquisition strategy, long-lead purchasing requirements, and commissioning/startup plans. Table 6 outlines the types of issues that need to be defined prior to detailed design. These are discussed in detail in the PDRI publications [Gibson and Dumont 1996a,b); and Gibson 1999].

Table 7. Twelve Common and Significant Scope Definition Elements, Industrial and Building Projects

Industrial projects	Building projects
Capacities	Facility requirements
Site characteristics available versus required	Evaluation of existing facilities
Project strategy	Business plan
Project design criteria	Project design criteria
Site location	Site layout
Social issues	Site selection considerations
Project objective statement	Project objective statement
Future expansion	Alteration considerations
Reliability philosophy	Reliability philosophy
Affordability/feasibility	Economic analysis
Environmental assessment	Environmental assessment
Project schedule	Project schedule

Table 8. Example of Comparable PDRI Scope Elements and their Descriptions

Scope element	Description
PDRI-Industrial: Element B3. Project strategy	Has a project strategy been defined that supports the market strategy in relation to the following items: (1) cost; (2) schedule; and (3) quality
PDRI-Buildings: Element A3. Business plan	A project strategy should be developed that supports the business justifications in relation to the following items: (1) funding availability; (2) cost and financing; (3) schedule milestones (including known deadlines); (4) types and sources of project funds; and (5) related/resulting projects.

Common Preproject Planning Scope Definition Elements

Many similarities exist in planning for different types of facilities. Organizational behavior and timely and appropriate input of key stakeholders is almost always one of the key ingredients. The general technical requirements are, in many cases, very similar as well, although the details may be different. The comparison outlined in subsequent paragraphs looks at industrial and building projects. It is not difficult to extend this line of reasoning to other types of projects, such as bridges, highways, pipelines, or water treatment facilities.

One can find similarities in scope definition elements by comparing the PDRI-Industrial and PDRI-Buildings. Because these two versions of PDRI are intended for different industry sectors, elements contained in each PDRI are designed to have different applicability. Industrial projects focus primarily on products, processes, and technologies, while building projects focus on the specific use of space and function. For example, "Process/Mechanical" is a major category in PDRI-Industrial but is not in the PDRI-Buildings. Additionally, PDRI-Industrial puts more emphasis on scope definition of instrumentation and electrical requirements. However, some of the scope definition elements are identically or similarly worded and can be applied during the planning and scope definition process regardless of the project type (Cho 2000).

PDRI-Industrial contains 70 scope definition elements, and PDRI-Buildings contains 64 scope definition elements, as described previously. Forty of the scope definition elements are similar. Cho (2000) identified 12 important scope definition elements that are applicable to both classes of projects (industrial and building); these are summarized in Table 7. The specific wording of the elements is in some cases different for the two PDRI versions (reflecting the focus of each tool), but the element pairs are comparable when examining the details of their application. An example of two comparable scope elements with descriptions is given in Table 8. Significant attention during preproject planning should be given to the elements listed in Table 7 in order to achieve project success, regardless of the project type.

Summary

Experienced practitioners in the construction industry realize that poor scope definition is one of the major factors leading to poor project performance. This article summarizes research conducted over the past 14 years, which provides solid evidence that thorough scope definition during the preproject planning process can significantly enhance the predictability of project outcomes, improve user satisfaction, and provide cost and schedule savings. More importantly, the key practices related to preproject planning have been identified.

When one is given the daunting task of planning for a capital facility, it may seem to be an overwhelming prospect. It certainly requires the active involvement of the facility owner, although many have little expertise in the construction process. Indeed, due to the iterative and often chaotic nature of facilities planning, many owners face such uncertainty that they skip the entire planning process and move to project execution, or decide to delegate the preproject planning process entirely to contractors, often with disastrous results. However, it is important to realize that many organizations have learned how to consistently and effectively plan capital facilities that meet their business needs.

The planning process for most capital projects is similar, but needs to be adapted to the conditions that are unique to a particular project and business circumstance. Certain common preproject planning issues should be addressed in order to achieve project success, whether the project is a commercial building or an industrial plant.

The following recommendations are provided to project management professionals, based on the results of numerous studies:

1. Commit to follow a standardized preproject planning process using experienced, technically proficient personnel. The facility owner organization must be the leader of this effort or, at a minimum, be integrally involved in this process.
2. Make sure that the project team is pursuing the "right" project in its work. The planning team must ensure that the project is aligned with business drivers. An understanding of organizational behavior, as well as sound technical skills and business acumen, are critical for successful planners at this stage.
3. The preproject planning process must generate the "right work product." Studies must be performed and scope definition documents prepared in order to facilitate a smooth transition from planning to design and construction. These scope definition documents generally relate to site assessment, equipment identification, flow design, and design parameters. Using checklists such as those outlined in this paper, or other planning tools, is essential to ensure that critical project scope risk issues are addressed.
4. The project team must choose the "right approach" to project execution during preproject planning. This task involves setting adequate cost and schedule baselines, choosing the right contracting strategy, focusing on the procurement process for long-lead items, and setting up a project control system.

Acknowledgments

The writers would like to thank the sponsors of the five research projects discussed in this paper, which were conducted during the past 14 years. The writers would also like to thank the many individuals who have participated in these studies through interviews, workshops, research teams, and by providing project data. Yu-Ren Wang, Chung-Suk Cho, and Michael P. Pappas were formerly graduate students at the University of Texas at Austin.

References

Cho, C. (2000). "Development of the project definition rating index (PDRI) for building projects." PhD thesis, Univ. of Texas, Austin, Tex.

Cho, C., Furman, J., and Gibson, G. (1999). "Development of the project definition rating index (PDRI) for building projects." *Research Rep. 155-11*, Construction Industry Institute, Austin, Tex.

Cho, C., and Gibson, G., Jr. (2001). "Building project scope definition using project definition rating index." *J. Archit. Eng.*, 7(4), 115–125.

Construction Industry Institute (CII). (1994). "Pre-project planning: Beginning a project the right way." *Publication 39-1*, Austin, Tex.

Construction Industry Institute (CII). (1995). "Pre-project planning handbook." *Special Publication 39-2*, Austin, Tex.

Dumont, P., Gibson, G., Jr., and Fish, J. (1997). "Scope management using the project definition rating index." *J. Manage. Eng.*, 13(5), 54–60.

Gibson, G. (1999). "PDRI: Project definition rating index, building projects." *Implementation Resource 155-2*, Construction Industry Institute, Austin, Tex.

Gibson, G., and Dumont, P. (1996a). "PDRI: Project definition rating index, industrial projects." *Implementation Resource 113-2*, Construction Industry Institute, Austin, Tex.

Gibson, G., and Dumont, P. (1996b). "Project definition rating index." *Research Rep. 113-11*, Construction Industry Institute, Austin, Tex.

Gibson, G., Jr., Kaczmarowski, J., and Lore, H., Jr. (1995). "Preproject-planning process for capital facilities." *J. Constr. Eng. Manage.*, 121(3), 312–318.

Gibson, G., Liao, S., Broaddus, J., and Bruns, T. (1997). "The University of Texas System capital project performance, 1990–1995." *Paper 97-1*, Office of Facilities Planning and Construction, Univ. of Texas, Austin, Tex.

Gibson, G. E., and Pappas, M. P. (2003). "Starting smart: Key practices for developing scopes of work for facility projects." *Federal Facilities Council Technical Rep. 146*, National Academies Press, Washington, D.C.

Griffith, A., and Gibson, G., Jr., (2001). "Alignment during preproject planning." *J. Manage. Eng.*, 17(2), 69–76.

Griffith, A., Gibson, G., Jr., Hamilton, M., Tortora, A., and Wilson, C. (1999). "Project success index for capital facility construction projects." *J. Perform. Constr. Facil.*, 13(1), 39–45.

Hamilton, M., and Gibson, G., Jr. (1996). "Benchmarking preproject-planning effort." *J. Manage. Eng.*, 12(2), 25–33.

Merrow, E. W., and Yarossi, M. E. (1994). "Managing capital projects: where have we been—where are we going?" *Chem. Eng.*, 101(10), 108–111.

O'Connor, J., and Vickroy, C. (1986). "Control of construction project scope." *Source Document 6*, Construction Industry Institute, Austin, Tex.

Shina, S. (1991). "Concurrent engineering: New rules for world-class companies." *IEEE Spectrum*, 28(7), 22–26.

Smith, M., and Tucker, R. (1983). "An assessment of the potential problems occurring in the engineering phase of an industrial project." *Rep. Prepared for Texaco, Inc.*, Univ. of Texas Austin, Tex.

Turino, J. (1991). "Concurrent engineering: Making it work calls for input from everyone." *IEEE Spectrum*, 28(7), 30–32.

Wang, Y. (2002). "Applying PDRI in project risk management." PhD thesis, Univ. of Texas, Austin, Tex.

附件二

Performance measurement in facilities management: driving innovation?

Michael Pitt and Matthew Tucker
School of the Built Environment, Liverpool John Moores University, Liverpool, UK

Received October 2005
Revised August 2007
Accepted May 2008

Abstract

Purpose – This paper aims to examine the state of knowledge of performance measurement in facilities management, in particular regarding the concepts underlying benchmarking in relation to its ability to drive innovation in the industry.

Design/methodology/approach – An evaluation of the key issues surrounding performance measurement and the effective application of benchmarking systems are examined, exploring the possibility of applying a benchmarking technique to measure facilities performance.

Findings – The paper suggests that a fully developed performance measurement solution via effective benchmarking can deliver as a business tool in facilities management (FM), whilst acting as a driver in the innovation process.

Practical implications – With the nature of performance measurement having changed over the past few decades, the paper acts as a catalyst to how performance measurement systems and techniques operate within FM and stimulate innovation.

Originality/value – By adopting the notion of innovation to performance measurement, the paper highlights new areas of thought to facilities management and how performance measurement is strategically applied to the industry.

Keywords Performance measures, Benchmarking, Facilities, Innovation

Paper type Research paper

Introduction

Performance measurement is an area to which companies have paid much attention recently. Performance is regarded as a major competitive issue (Tranfield and Akhaghi, 1995). In facilities management (FM), there is a wide range of choices in measuring FM performance, reflecting the varied nature of the field. The focus on FM skills and techniques should be in the areas that contribute to the overall management of a business, financial and personal criteria (Barrett, 1992). This paper aims to review the state of knowledge of performance measurement in FM and seeks to explore how measuring service performance is linked to innovation processes within the organisation.

Benchmarking is a key performance measurement tool that allows organisations to achieve added value and "superior performance" (Camp, 1989). The discussion focuses on the proposition of adopting benchmarking techniques in measuring facilities performance, driving a framework of an FM performance measurement solution. It is important to stress however that by researching such an approach, with the emphasis on benchmarking, it does not contend that benchmarking should be the only performance instrument implemented to organisational performance measurement

Property Management
Vol. 26 No. 4, 2008
pp. 241-254

0263-7472
DOI 10.1108/02637470810894885

systems. It merely identifies the importance of benchmarking as a stimulant to achieving innovation in performance measurement.

Facilities management overview

FM is a relatively new discipline. It has developed since around 1978 where the Herman Miller Corporation, the worlds leading furniture manufacturer, staged a conference on "Facilities Impact on Productivity". This might be seen as the beginning of FM. FM as a discipline emerged out of practice, just as the great established professions. It emerged with the integration of three main strands of activity: property management, property operations and maintenance and office administration (Kincaid, 1994). More significantly it established a focus on the management and delivery of the business "outputs" of both of these entities; namely the productive use of building assets as workplaces (Varcoe, 2000).

The International Facility Management Association (IFMA) and the British Institute of Facilities Management (BIFM) adopt the following definition, "the practise of coordinating the physical workplace with the people and work of the organisation: it integrates the principles of business administration/architecture/behaviour/ engineering science" (US Library of Congress).

FM can be defined as the integration and alignment of the non-core services, including those relating to premises, required to operate and maintain a business to fully support the core objectives of the organisation. Over the years, FM has been growing as a business field and also as a scientific discipline, slowly finding and anchoring its position among organisations' business processes. Nowadays, the dedication of FM organisations to new developments and continuous innovation processes seems to be the way to stay in business, constantly exceeding customers' expectations and adding value to the core business of the client organisation (Mudrak *et al.*, 2004).

Performance measurement principles and revolution

The traditional view determined by Teague and Eilon (1973) of performance measurement is that it has three broad purposes:

(1) to ensure the achievement of goals and objectives;

(2) to evaluate, control and improve procedures and processes; and

(3) to compare and assess the performance of different organisations, teams and individuals.

An early attempt at developing financial measures was made by Du Pont (Walters, 1997). Du Pont is widely acknowledged as being the founder of financial performance measurement, by introducing a pyramid of financial ratios as early as 1903. However, in the late 1970s and 1980s, numerous authors expressed a general dissatisfaction with traditional backward looking or lag accounting based performance measurement systems. In the 1990s, attention on performance measurement shifted to quality and consumer satisfaction. A broader conceptualisation of business performance emerged, as the emphasis on operational performance (i.e. non-financial performance) was added to indicators to measure business performance (Venkatraman and Ramanujam, 1986).

Traditionally the use of financial indicators has determined the way in which businesses operate -- if the cost is low, and the profit is high then they are happy. With the considerable influence of the changing business marketplace however, this philosophy is no longer sustainable, and the emergence of non-financial or qualitative indicators, specifically focused on process, structure and change, instead of traditional cost, profit, and output, has drastically changed the way in which businesses perceive performance.

Drucker (1993) described traditional measures as not adequate for business evaluation and fail to meet new business needs as they are lagging indicators. By this, they mean that traditional indicators are not able to provide real time performance, they are always set on past periods. This was reiterated by Varcoe (1996) terming traditional indicators as being "past their sell by date". Kaplan and Norton (1996) contended that "companies were in the midst of a revolutionary transformation" as they shifted from industrial age competition to information age competition. By this, they urged that it was no longer feasible to gain "competitive advantage" within business merely through the deployment of new technology (Kaplan and Norton, 1996). To this, a shift has occurred, as Kaplan and Norton (2001) claim that financial measures are historical in nature, they report only on outcomes and the consequences of past actions. Amartunga and Baldry (2003) summarised the views advanced in the debate on traditional performance measurement as follows:

- Criticism of traditional management control (Brown and Laverick, 1994; Stone, 1996; Letza, 1996; Rangone, 1997; Neely, 1998).
- Need to represent non-financial measures (Olve *et al.*, 1999; Ernst & Young, 1998).
- Lack of prescription on how to implement the measures (Olve *et al.*, 1999; McFadzean, 1995).
- Lack of strategic focus (Hally, 1994).

The debate and the criticism on traditional performance measurement show that financial performance measures are not a solution to the measurement of business performance. Therefore the principles of performance measurement become revolution, as contemporary ideas and practices of how to strategically measure business performance change. For Nani *et al.* (1990) performance measurement systems were developed as a means of monitoring and maintaining organisational control:

> Organisational control may be defined as the process of ensuring that an organisation pursues strategies that lead to the achievement of overall goals and objectives.

Hronec's (1993) work emphasises this, defining performance measures as a vital sign of the organisation, showing how well activities within a process or the outputs of a process achieve a specific goal. According to Zairi (1994) performance measurement is the systematic assignment of a number of activities. Kanter (1995) claims that in today's dynamic business environment the emphasis has shifted to the "three C's" – concepts, competence, and connections, which drives from investments in innovation, education and collaboration. As cited in Wilson (2000), the roles of performance measurement have been intertwined with the premise that organisations achieve success (meet their objectives) by delivering services with greater efficiency and effectiveness than their competitors (Ghobadian and Ashworth, 1994).

Further themes emerging in contemporary academic literature that relate to adding value to performance measurement systems have been determined and analysed by Wilson (2000). The themes are:

- *Measurement for improvement*, which states that measurement systems are service functions and only have the right to exist if they add value to the organisation (Van Schalkwyk, 1998).
- *The integration of broad measures*, which see the challenge for performance measurement systems as being the ability to balance multiple measures (i.e. cost, quality and time) across multiple levels (i.e. the organisation, the process and the people) (Hronec, 1993).
- *Clear communication and dissemination*, where, if information is poorly presented, it may be misunderstood, poorly assimilated or at the extreme completely ignored (Harvey, 1984).

Research by Amartunga and Baldry (2003) described performance measurement as a process of assessing progress towards achieving pre-determined goals, including information on the efficiency by which resources are transformed into goods and services, the quality of these outputs and outcomes, and the effectiveness of organisational objectives. Therefore, the basic foundations of performance measurement are the qualifications of elements, which impact on organisational objectives, management control and evaluation.

Fitzgerald *et al.* (1991) examined performance measurement in service businesses. They highlighted the complexity of measuring performance within the service sector, as opposed to that of the manufacturing sector, as services are intangible in nature. For example, Fitzgerald *et al.* (1991) talk about air travel where there are many intangible factors such as the helpfulness of the cabin crew, but also more tangible factors, such as the measure of luggage with passengers. Fitzgerald *et al.* (1991) contended therefore that "a range of measures" is required, which act as a "contingency theory" to the uniqueness of performance measurement within the service sector. Fitzgerald *et al.* (1991) stressed however that the selection of a range of performance measures should be made according to the strategic intentions of the organisation. What this means in essence is that measures should have a balance so that one dimension is not dominating the performance system and consequently skewing the strategic goals of the organisation.

Facilities performance and innovation

The objectives and roles of performance measurement to achieve organisation goals have been expounded as FM is growing and enhancing into this business. However, as business performance becomes revolution, the need for learning, growth, and innovation becomes crucial.

There are as many definitions of innovation as there are of FM. Innovation can be defined as a continuous process of bringing new ideas into practical uses (Tidd *et al.*, 2001). A broad definition as cited in Mudrak *et al.* (2004) is that innovation is:

> a management process, involving multiple activities, performed by multiple actors from one or several organisations, during which new combinations of means and/or ends, which are new for creating and/or adopting a unit, are developed and/or produced and/or implemented and/or transferred to old and/or new market-partners.

According to Tidd *et al.* (2001) the innovation processes in product and service development are similar in principle; however, they vary in specific routines and activities performed, by which the innovation processes are enabled. One of the more common debates concerning the definition of innovation asks whether innovation should be regarded as a process or a discrete event (Cooper, 1998).

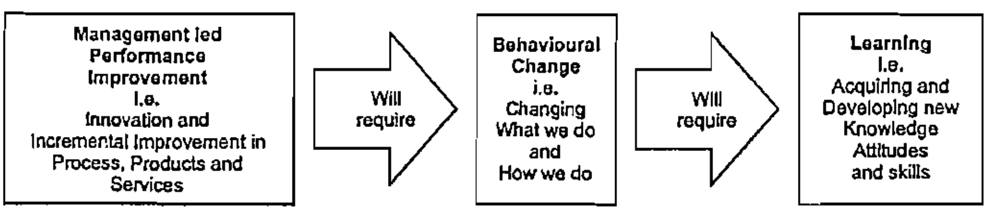
Either a process or discrete event, innovation is a synergised element to organisation growth and competition in the market. According to Cooper (1998) understanding of learning processes is a key requirement for the facilitation and optimisation of improvement and innovation in business processes. By understanding and optimising learning processes, managers in organisations will be able to achieve behavioural change leading to performance measurement. With respect to performance measurement and the innovation process in organisations' it shows that performance measurement is the driver.

Buckler (1998) explained the link between learning and performance improvement and stated that by understanding and optimising learning process, managers will be able to achieve behaviour change leading to performance improvement (Figure 1). Therefore the growth in performance measurement within the FM discipline seems to relate and directly impact on the organisations performance and actual innovation of that performance.

Facilities performance measurement

The focus of facilities management skills and techniques should be in the area that contributes to the overall management of a business by relating accommodation and support infrastructure issues to business, financial and personal criteria (Barrett, 1992). Therefore the issue of measuring facility performance is a critical task to the facilities manager. However, why should FM organisations want to measure performance? From a classical management perspective there is a need to assess performance in order to guide management decision-making, and as FM is a subset of general management, performance measurement applies to management in the FM context (Amaratunga *et al.*, 2000). Further, performance measurement is a driver to an innovation process in an organisation.

Alexander (1996) identifies measurement of performance as one of the "three essential issues for the effective implementation of a facilities strategy". Thus



Source: Buckler (1998)

Figure 1. The link between learning and performance improvement

performance measurement has become increasingly important both for reasons of justification to general management and to support management and practise within FM organisations. The measurement of facilities has three main components, namely, physical, functional, and financial (Williams, 1996). Physical performance relates to the behaviour of the building fabric and embraces physical properties such as structural integrity, heating, lighting, energy efficiency, maintainability, and durability. Functional performance concerns the relationship of the building with its occupiers and embraces issues such as space, layout, ergonomics, image, ambience, communication, health and safety, and flexibility. Finally, financial performance arises from the physical and functional performances of the building and comprises capital and recurrent (life-cycle) expenditures, depreciation and efficiency of use etc.

According to Amartunga and Baldry (2003), the contribution made by FM will be judged by organisations' stakeholders over a wide range of performance criteria, including the hard metrics of finance and economics. FM is seen to be able to contribute to the performance of an organisation in many ways, including strategy, culture, control of resources, service delivery, supply chain management, and perhaps most importantly, the management of change. Quality, value and the management of risk also emerge as significant factors. Thus it is important to have systems to measure the effect of the FM functions on an organisations core business, together with systems to measure FM's own performance.

There is a wide range of choices in measuring FM performance reflecting the varied nature of the field, and is regarded as a major competitive issue (Kincaid, 1994). Facilities managers must understand the nature and the business of the organisation and their work process in order to derive the effective and efficient measurement tools. Besides this, the facilities manager may also have to clarify the purposes of measurement before deciding on the technique to be applied for assessing facilities management performance.

Measuring facilities performance: a practical insight

The key determinant in achieving effective performance measurement is to view FM strategically, where FM is aligned to support the core objectives of the organisation. To exemplify how this may operate practically, let us take one element of FM, the reception service. The reception service is at the front-line of the business. Often it is the first service that the customer comes in contact with, and consequently has a significant impact on their initial perception of the organisation. One could assume therefore that the most efficient method to measure the performance of the reception service is through customer satisfaction indicators. However, is this comparable for all organisations? Here is where FM performance measurement must be viewed from a strategic context.

This can be further exemplified by comparing three different organisations delivering a reception service. Firstly, the reception service within a telecommunications office. Primarily, the core business objectives within the telecommunications industry are centred on the customer through the delivery of a product. All business operations must meet the needs of the customer in order to generate mass customer satisfaction and stimulate market sales. Hence, when measuring the efficiency of the reception service within a telecommunications office, the primary indicators will be focussed on customer satisfaction, such as the helpfulness of staff, the ability of staff to deal with a query, and the comfort of the waiting area.

Second, the reception service within an international bank. Again, primarily core objectives if an international bank are centred on the customer, in this case however through the delivery of financial support and management. Here, the core business objectives differ slightly, as the bank is still primarily selling services to the customer and therefore needs to promote high levels of customer satisfaction, but also has an important security element involved due to the nature of the core business. When measuring the efficiency of the reception service within the bank, the indicators will be different, focussed around two key factors – ensuring high levels of customer satisfaction, and ensuring security measures are in place when dealing with customers. This is likely to involve ensuring that standard identification checks are taking place, such as cross-checking personal details within a database.

Third, the reception service within a government security building. Here, the core business objectives differ dramatically to the previous two examples, as the primary focus is centred on security. In this instance, measuring the levels of customer satisfaction of the reception service fall much further down the list of priority indicators, and are overtaken with robust security measures ranging from ensuring that standard identification checks are taking place, to more sophisticated measures involving rigorous scanning and checking of visitors entering and exiting the building.

Through using the example of one element of FM, it illustrates the importance of how the practical application of performance measurement must be centred on the core business objectives of that organisation. FM performance measurement however is often too internally focussed. Measures can therefore be benchmarked in order to understand how an organisation is performing compared to industry overall. However, the scope of benchmarking data depends heavily on the diversity and depth of the particular sector in which the organisation functions. From the examples above, benchmarking reception performance is much more accessible in the first two examples. However, obtaining benchmarking data on high level security buildings is more difficult. The paper now seeks to understand how benchmarking can be used as a tool to measure facilities performance, and what impact this can have on driving innovation in FM performance measurement.

Using benchmarking as a tool to measure facilities performance

Benchmarking is essentially a cost reduction method (McDougall and Hinks, 2000). The principle of benchmarking evolved out of the total quality management movement and allows managers to place their performance measurement in context (Camp, 1989). It is the most powerful technique for gaining and maintaining competitive advantage (Codling, 1992). Sarkis (2001) outlines that from a managers perspective, benchmarking has been defined as a continuous, systematic process for evaluating the products, services and work processes of organisations that are recognised as representing best practices, for the purposes of the organisations' improvement.

For Camp (1989), benchmarking in the first instance is about practices, not metrics. Many immediately consider benchmarking as a set of outputs, just like many confuse innovation as a one off invention instead of a process. Benchmarking is not as simple as gathering indicators together so an organisation can evidence that they are measuring something. Because what are they measuring, and how relevant is it to their overall objectives? Hence, there must be a meaning before the measurement, a process before the output, or in Camp's case, a practice before the metric. To this, Camp defines benchmarking as follows:

> Benchmarking is the search for industry best practices that lead to superior performance.

In order to achieve this, Camp identifies four basic steps that are fundamental to benchmarking success:

(1) *Know your operation* – evaluate internal operation strengths and weaknesses.

(2) *Know the industry leaders or competitors* – know the strengths and weaknesses of the competition.

(3) *Incorporate the best* – emulate the strengths of the leaders in competition.

(4) *Gain superiority* – go beyond the best practices installed and be the best of the best

Hence, benchmarking techniques can significantly help FM organisations to gain "superiority", and can significantly drive innovation in their performance measurement systems. Benchmarking within FM began to take shape in 1984, where the IFMA started to collect data on facilities trends and demographics. This was expanded in 1987 to include occupancy costs, which coincided with the initial interest in such data in the UK (Varcoe, 1996). In FM, benchmarking as a performance measurement technique is now well known however, and the application of benchmarking to FM performance criteria is now apparent within large organisations (McDougall and Hinks, 2000). It is the ideal tool for setting corporate goals and transforming them into tangibles which are delivered to the end customer and it is the tool that enables the senior manager to answer questions such as: where are we now? Where do we need to be? How do we get there? How could we remain there? The desired standards of performance are therefore to optimise process performance in order to deliver total quality and 100 per cent value to the end customer (Zairi, 1994).

Gilleard and Yat-Lung (2004) stated that FM benchmarking issues are typically driven by financial, organisational, change management, and customer-related needs. They may be either internally focussed or external driven. Therefore it has put pressure on FM teams that value customer-driven issues such as delivery of quality and timely services. It also fails to take into account how an organisation performs at a strategic level, whether from the worker or the workplace perspective. The Department of Trade and Industry (DTI, 1993) produced an executive guide and point out the importance of benchmarking against:

- The best you can find whether within your industry or outside.
- What is relevant to your customers view of what is important.
- That thing that affects financial performance.

From an FM context, many people think that benchmarking is only about comparing cost levels. However Wauters (2005) revealed there are other aspects of FM that can be benchmarked. The most prominent of these aspects are:

- *Space use*: Benchmarking the space use is a prime aspect as it drives all of the premises costs. The floor areas need to be known for the purpose of comparing costs of maintenance, cleaning etc;

- *FM management*: Benchmarking the effectiveness and cost of the facilities management operation on a strategic/tactical level; and
- *Computer-aided FM systems*: Benchmarking of the costs and effectiveness of the help desk.

In addition, Hinks and McNay (1999) emphasise the need to measure performance gaps between service delivery and customer satisfaction. Hence, Hinks and McNay stress the need to rank benchmarking criteria, linking these to performance and service in such a way that their overall influence may be evaluated against business-driven imperatives. Further, Hinks and McNay suggest that the application of a manage-by-variance tool. The tool identifies business and facility key performance indicators (KPI), helping to create a rank order among the benchmarking criteria. Further literature on benchmarking techniques focused within the FM discipline has come from Wauters (2005), Gilleard and Yat-Lung (2004), Loosemore and Hsin (2001), Massheder and Finch (1998), Akhlagi (1997) and Varcoe (1996). According to Wauters (2005) benchmarking is one of the techniques that has been used by many organisations and if applied correctly will lead to effective value management of facilities services. By this Wauters means that to use benchmarking effectively, you must identify the "ideal performance", and then emulate it.

Benchmarking and service performance in FM

Most services are provided through facilities (Brackertz and Kenley, 2002) and it has been suggested that the measurement of facilities should relate to the core business objectives such as customer satisfaction or service delivery (e.g. Walters, 1999; Tucker and Smith, 2008). As an integrated approach in managing the workplace, service is one of the key components facilities managers put forward and seriously consider in achieving the set-up goals of the organisation. In service provision, FM is wide in scope, concerned with the major strategic decisions to the very detailed decisions such as posting the signs to the ladies' toilet in a restaurant (Looy *et al.*, 2003). Therefore, in order to achieve organisational objectives, measuring service performance is crucial to the facilities manager.

However, applied models that link facilities performance measurement to organisational strategy have to date, been limited (Brackertz and Kenley, 2002). It has been noted that in service firms, the importance of the physical setting depends on the nature of the job as well as the consumption experience. Consequently, she presented a typology of service environments or "servicescapes", being those categories of a service based on who is performance in the servicescape (the customer, employees, or both) as well as the complexity of the servicescape. According to Looy *et al.* (2003), the customer perceives the servicescape holistically. They suggest the environmental dimensions where customers value the service. Environmental dimensions comprise ambient conditions, spatial layout and process, and sign, symbols and artefacts (Figure 2).

Ambient conditions refer largely to background characteristics such as noise, temperature and scent. In short, all the elements of our human environment affect the human five senses. Spatial layout and process includes elements of the environment that are closely related to the core elements of service delivery. These dimensions refer to the way of arrangement and the physical and psychological effects on the customer.

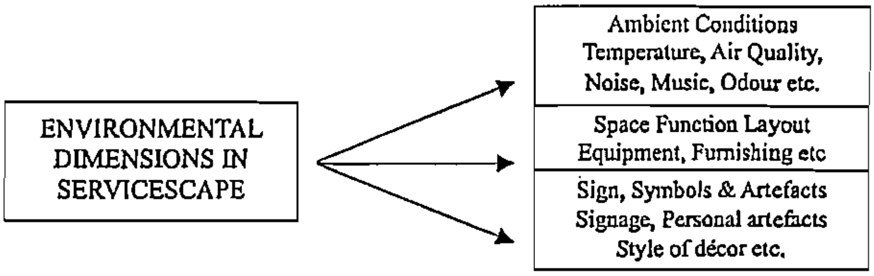


Figure 2.
Servicescape environment

Source: Looy *et al.* (2003)

The other dimension relates to sign, symbols and artefacts. It is the item in the physical environment that serves as explicit or implicit communications to its users about the place.

Tucker and Smith (2008) explored the importance of user perceptions within an organisational context, and how their perceptions can be evidenced and applied within FM. Tucker and Smith contended that there is a "logical customer performance ladder" (LCPL) that organisations should aspire to climb in order to achieve optimum levels of service delivery (Figure 3). The ladder acknowledges the importance of the initial user input to determine innovative ways of delivering what is important; to the internal business processes that will enable this delivery to be successful; to the strategic direction of the performance measures in line with their core business objectives; and to the consequent added value by increased customer satisfaction.

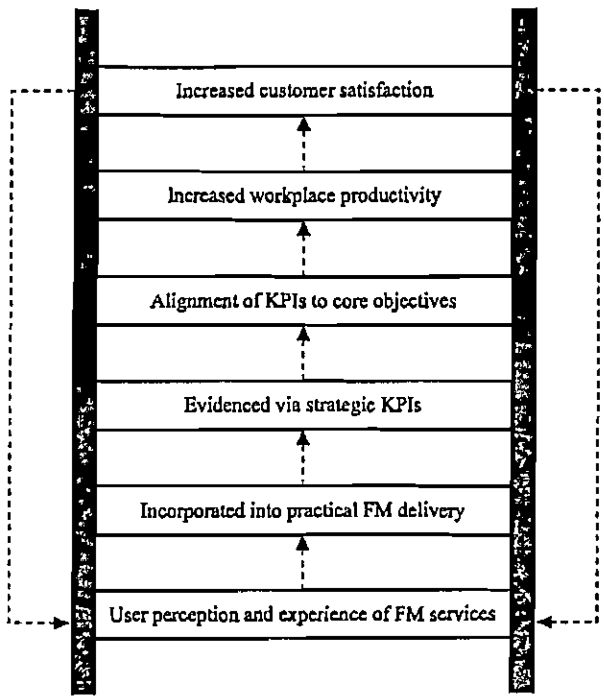


Figure 3.
Logical customer performance ladder

Source: Tucker and Smith (2008)

Performance measurement is integral to the effective implementation of continuous improvement and added value within business (Tucker and Pitt, 2008a) and can act as a key driver for embedding innovation into the mindset. Tucker and Pitt (2008a) illustrate the importance of incorporating a performance-focused strategic concept in FM (Figure 4), emphasising that in order to achieve strategic FM, organisations should incorporate performance measurement through a balance of competitive service delivery and the application of best value principles, which will in turn feed directly into the core objectives of the organisation.

Research in benchmarking and innovation in FM

Generally the review of the literature has determined the area of proliferation in measuring FM performance. Measuring facilities performance contributes to the organisational successfulness to the innovation process. Benchmarking is among the accepted approaches involved in measuring "hard" and "soft" issues in facilities performance without denying the weaknesses of the technique itself. Hence, the innovation process of performance measurement systems, can be significantly enhanced via the application of effective benchmarking techniques. Focusing on measuring service performance in a facilities context, benchmarking seems to be an approach to be considered. However, questions to be asked as an ongoing research project before applying a benchmarking technique are as follows:

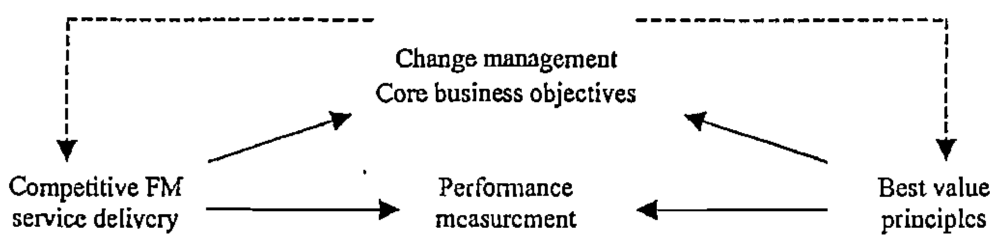
(1) How do customers value the service performance and how is it distinct from the service itself?

(2) What are the mechanisms to measure the service performance and how is it measured?

(3) How does one differentiate between the appreciation of service provided and the physical environment?

These questions and the general application of benchmarking and achieving customer satisfaction and added value within organisational performance measurement systems form the basis for the authors' further research in this area.

An example of this is through Tucker and Pitt (2008b) attempting to enhance the level of performance measurement sophistication in FM by filling the existing void of strategically applying customer satisfaction systems. Tucker and Pitt are implementing a strategic management approach to develop a customer performance measurement system (CPMS). The concept of the CPMS is to integrate generic industry benchmarks into a customised organisation framework in order to kick-start a gap



Source: Tucker and Pitt (2008a)

Figure 4. Performance-focused strategic FM

analysis process and stimulate continuous improvement. It is hoped that in turn this research will generate innovation within FM by applying performance measurement strategically.

Conclusions

Performance measurement is an established concept that has taken on renewed importance in varieties of organisations. In FM, performance measurement is important to contributing to organisational success in terms of effectiveness, efficiency-adding value. The review of the literature suggests that the key components that impact on FM implementation are the synergistic blend of "hard" and "soft" issues. The principle of benchmarking seems to be techniques that can be applied in measuring facilities service performance and a catalyst in generating innovation to the performance process. It is important to highlight that the characteristic of the services itself are very subjective to measure, and the acknowledgement that benchmarking should not be the only performance mechanism within an organisations overall system. However it does suggest that benchmarking techniques are sparse and can directly generate innovation processes to performance in FM. Hence, the questions put forward will be scrutinised in whole or in part through further extensive research.

References

Akhlaghi, F. (1997), "How to approach process benchmarking in facilities management: catering services in the UK National Health Service", *Facilities*, Vol. 15 Nos 3/4, pp. 57-61.

Alexander, K. (1996), *A Strategy for Facilities Management: Theory and Practice*, E & FN Spon, London.

Amaratunga, D. and Baldry, D. (2003), "A conceptual framework to measure facilities management performance", *Property Management*, Vol. 21 No. 2, pp. 171-89.

Amaratunga, D., Baldry, D. and Sarshar, M. (2000), "Assessment of facilities management performance – what next?", *Facilities*, Vol. 18 Nos 1/2, pp. 66-75.

Barrett, P. (1992), "Development of a post-occupancy building appraisal model", in Barrett, P. (Ed.), *Facilities Management: Research Directions*, RICS Books, Coventry.

Brackertz, N. and Kenley, R. (2002), "A service delivery approach to measuring facility performance in local government", *Facilities*, Vol. 20 Nos 3/4, pp. 127-35.

Brown, D.M. and Laverick, S. (1994), "Measuring corporate performance", *Long Range Planning*, Vol. 27 No. 4, pp. 89-98.

Buckler, B. (1998), "Practical steps towards a learning organisation: applying academic knowledge to improvement, an innovation in business process", *The Learning Organization*, Vol. 5 No. 1, pp. 15-23.

Camp, R.C. (1989), *Benchmarking – The Search for Industry Best Practices that Lead to Superior Performance*, ASQC Quality Press, New York, NY.

Codling, S. (1992), *Best Practice Benchmarking. A Management Guide*, Gower, Aldershot.

Cooper, J.R. (1998), "A multidimensional approach to the adoption of innovation", *Management Decision*, Vol. 36 No. 8, pp. 493-502.

Drucker, P.F. (1993), "We need to measure, not count", *Wall Street Journal*, April 13, Section A, p. 18.

DTI/CBI (1993), *Best Practice Benchmarking: An Executive Guide*, Department of Trade and Industry, London.

Ernst & Young LLP (1998), *Measures that Matter*, Ernst & Young Centre for Innovation, London.

Fitzgerald, L., Johnston, R., Brignall, S., Silvestro, R. and Voss, C. (1991), *Performance Measurement in Service Businesses*, CIMA, Black Bear Press Ltd, Cambridge.

Ghobidian, A. and Ashworth, J. (1994), "Performance measurement in local government – concept and practice", *International Journal of Operations & Production Management*, Vol. 14 No. 5, pp. 35-51.

Gilleard, J.D. and Yat-Lung, P.W. (2004), "Benchmarking facility management: applying analytic hierarchy process", *Facilities*, Vol. 22 Nos 1/2, pp. 19-25.

Hally, D.L (1994), "Accounting for the 1990s", *Finance*, December, pp. 129-82.

Harvey, M. (1984), "Balancing facts against figures", *Certified Accountant*.

Hinks, J. and McNay, P. (1999), "The creation of a management-by-variance tool for facilities management performance assessment", *Facilities*, Vol. 17 Nos 1/2, pp. 31-53.

Honrec, S.M. (1993), *Vital Signs – Using Quality, Time and Cost Performance Measurements to Chart Your Company's Future*, AMACOM, New York, NY.

Kanter, R.m. (1995), *World Class: Thriving in the Global Economy*, Simon & Schuster, New York, NY.

Kaplan, R.S. and Norton, D.P. (1996), *The balanced Scorecard: Translating Strategy into Action*, Harvard Business School Press, Boston, MA.

Kaplan, R.S. and Norton, D.P. (2001), "Transforming the balanced scorecard from performance measurement to strategic management: part 1", Vol. 15 No. 1, American Accounting Association Accounting Horizons, March, pp. 87-104.

Kincaid, D.G. (1994), "Measuring performance in facilities management", *Facilities*, Vol. 12 No. 6, pp. 17-20.

Letza, S.R. (1996), "The design and implementation of the balanced business scorecard: analysis of three companies in practice", *Business Process Re-engineering & Management Journal*, Vol. 2 No. 3, pp. 54-76.

Loosemore, M. and Hsin, Y.Y. (2001), "Customer-focused benchmarking for facilities management", *Facilities*, Vol. 19 Nos 13/14, pp. 464-75.

Looy, B.V., Gemmel, P. and Dierdonck, R.V. (2003), *Service Management and Integrated Approach*, Financial Times/Prentice-Hall, London.

McDougall, G. and Hink, J. (2000), "Identifying priority issues in facilities management benchmarking", *Facilities*, Vol. 18 Nos 10/11/12, pp. 427-34.

McFadzean, E. (1995), *Relating Facilities Management to Organisational Performance*, Centre for Facilities Management, University of Strathclyde, Strathclyde.

Massheder, K. and Finch, E. (1998), "Benchmarking methodologies applied to UK facilities management", *Facilities*, Vol. 16 Nos 3/4, pp. 99-106.

Mudrak, T., Wagenburg, A.V. and Wubben, E. (2004), "Assessing the innovative ability of FM teams: a review", *Facilities*, Vol. 22 Nos 11/12, pp. 290-5.

Nani, A.J., Dixon, J.R. and Vollmann, T.E. (1990), "Strategic control and performance measurement", *Journal of Cost Management*, Summer, pp. 33-42.

Neely, A.D. (1998), *Performance Measurement: Why, What and How*, Economics Books, London.

Olve, N., Roy, J. and Wetter, M. (1999), *Performance Drivers: A Practical Guide to Using the Balanced Scorecard*, John Wiley & Sons, Chichester.

Rangone, A. (1997), "Linking organisational effectiveness, key success factors and performance measures: an analytical framework", *Management Accounting Research*, Vol. 8 No. 2, pp. 207-19.

Sarkis, J. (2001), "Benchmarking for agility", *Benchmarking: An International Journal*, Vol. 8 No. 2, pp. 88-107.

Stone, C.L. (1996), "Analysing business performance: counting the 'soft' issues", *Leadership & Organization Development Journal*, Vol. 17 No. 4, pp. 21-8.

Teague, J. and Eilon, S. (1973), "Productivity measurement: a brief survey", *Applied Economics*, Vol. 5 No. 2, pp. 133-45.

Tidd, J., Beasant, J. and Pavitt, K. (2001), *Managing Innovation: Integrating Technological, Market and Organisational Change*, Wiley, Chichester.

Tranfield, D. and Akhlaghi, F. (1995), "Performance measures: relating facilities to business indicators", *Facilities*, Vol. 13 No. 3, pp. 6-14.

Tucker, M. and Pitt, M. (2008a), "Innovative customer performance measurement and benchmarking", paper presented at European Facilities Management Conference 2008, Manchester, June.

Tucker, M. and Pitt, M. (2008b), "Update on the development of a customer performance measurement system (CPMS) for facilities management: enabling generic market benchmarks", paper presented at CIB 070 Conference 2008, Edinburgh, June.

Tucker, M. and Smith, A. (2008), "User perceptions in workplace productivity and strategic FM delivery", *Facilities*, Vol. 26 Nos 5/6, pp. 196-212.

Van Schalkwyk, J.C. (1998), "Total quality management and the performance measurement barrier", *The TQM Magazine*, Vol. 10 No. 2, pp. 124-31.

Varcoe, B.J. (1996), "Facilities performance measurement", *Facilities*, Vol. 14 Nos 10/11, pp. 46-51.

Varcoe, B.J. (2000), "Implications for facility management of the changing business climate", *Facilities*, Vol. 18 Nos 10/11/12, pp. 383-91.

Venkatraman, N. and Ramanujam, V. (1986), "Measurement of business performance in strategy research: a comparison of approach", *Academy of Management Review*, Vol. 11 No. 4, pp. 801-14.

Walters, D. (1997), "Developing and implementing value-based strategy", *Management Decision*, Vol. 35 Nos 9/10, p. 709-12.

Walters, M. (1999), "Performance measurement systems – a study of customer satisfaction", *Facilities*, Vol. 17 Nos 3/4, pp. 97-104.

Wauters, B. (2005), "The added value of facilities management: benchmarking work processes", *Facilities*, Vol. 23 Nos 3/4, pp. 142-51.

Williams, B. (1996), "Cost-effective facilities management: a practical approach", *Facilities*, Vol. 14 Nos 5/6, pp. 26-38.

Wilson, A. (2000), "The use of performance information in the management of service delivery", *Marketing Intelligence & Planning*, Vol. 18 No. 3, pp. 127-34.

Zairi, M. (1994), "Benchmarking: the best tool for measuring competitiveness", *Benchmarking for Quality Management & Technology*, Vol. 1 No. 1, pp. 11-24.

Corresponding author
Michael Pitt can be contacted at: m.r.pitt@ljmu.ac.uk