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PERFORMANCE OF CRUCIFORM COLUMN USING UNIVERSAL BEAM SECTIONS UNDER AXIAL COMPRESSION LOAD

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Abstract. The main function of a column is to transfer loads by means of compressive action. The response of the column to a nominally applied load depends upon a number of factors. The most important are its length and cross-sectional shape, the strength of material, the conditions of support provided at its ends and the method of restrained to its axis. This paper presents the performance of cruciform column under axial compression load. Cruciform column, which is also known as compound members, consists of two universal beams section where one universal beam section is cut into two at the mid section of the beam and welded to the other beam section. The compression capacity tables based on the code BS5950-1:200 are developed for columns with different sections and different effective lengths. The study shows that the compression resistance of the column increases as the radius of gyration of the section increases due to the formation of cruciform column. The study also concludes that the use of cruciform column contributes to the saving of the column steel weights up to 35% compared to UC sections and up to 60% as compared to UB sections.

Keywords: Cruciform column, compound member, compression resistance, effective length, universal beam

Abstrak. Tujuan utama penggunaan tiang adalah untuk mengagihkan beban dengan cara tindakan mampatan. Daya mampatan tiang bergantung kepada beberapa faktor. Antara yang paling penting ialah panjang efektif, luas keratan, kekuatan bahan, sambungan pada kedua-dua hujungnya dan juga rembatan pada paksi lenturannya. Kertas kerja ini membincangkan keupayaan mampatan tiang *cruciform*. Tiang *cruciform* juga dikenali sebagai tiang gabungan, terdiri daripada dua keratan rasuk semesta di mana satu keratan rasuk semesta dikerat di tengah keratan dan dikimpal pada satu keratan rasuk semesta lain. Jadual keupayaan mampatan telah dihasilkan untuk pelbagai jenis saiz tiang dengan panjang efektif yang berbeza. Semua pengiraan untuk jadual keupayaan mampatan adalah merujuk kepada BS 5950-1:2000. Daripada kajian ini, didapati bahawa kekuatan mampatan tiang bertambah dengan pertambahan jejari legaran. Kajian ini dapat menyimpulkan bahawa penggunaan tiang *cruciform* mengurangkan jumlah berat tiang sebanyak 35% apabila dibandingkan dengan tiang universal dan 60% apabila dibandingkan dengan rasuk universal.

Kata kunci: Tiang *cruciform*, tiang gabungan, kekuatan mampatan, panjang efektif, rasuk universal

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1.0 INTRODUCTION

Columns are generally referred to as vertical compression members that support floors or roofs in structural frames. In many cases, such members are subjected to both axial and bending effects. In practice, most columns generally fail due to either local buckling or overall buckling or the combination of both. For short column, the failure is usually due to local buckling where the mode of failure is known as squashing. However, slender column normally fails at elastic critical loads which usually located at the mid-length of the column with curved shape type of failure. In practice, however, the mode of failure usually encountered in the design of column is within the range of these two conditions. The mode of failure does not only depend on the length of the column but also on its cross sectional area that determines the slenderness ratio of the column. Slenderness is defined as the ratio of column length over minimum radius of gyration. The compression resistance of the column is therefore, very much dependent on the effective length and the cross sectional area of the section. A typical column known as universal column of H-shaped section is usually used in the design of steel column, but due to the problem of weak axis, the compressive resistance of the column is greatly reduced. Therefore, cruciform column using universal beam section is introduced as an alternative section to increase the compressive resistance of the column.

2.0 FORMATION OF CRUCIFORM COLUMN WITH UNIVERSAL BEAM SECTIONS

Cruciform column is made of two universal beams where one beam is cut at mid-length and attached to the other beam by means of a fillet weld, as shown in Figure 1. This fillet weld should be stronger than the parent materials that are welded together. In order to achieve this strength, the size of effective weld (i.e. 0.7 multiplied by the

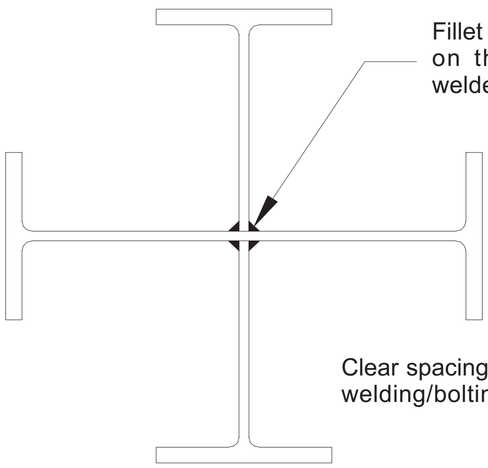


Figure 1 Cruciform column with universal beam sections

size of weld) should be greater than the thickness of the welded column web. In case of cruciform column, the weld is usually welded on both sides to form a symmetrical section. As a result, a cruciform shape is developed so that the value of moment of inertia in the x-axis and the y-axis is the same. The use of universal beam instead of universal column section for the formation of the cruciform column section is recommended due to the geometrical aspects of universal beam. Factors including greater stiffener on major axis and that adequate space between the beam flanges to carry out the process of fabrication and installation of the beam to column connection make the universal beam a better choice.

3.0 DETERMINATION OF COMPRESSIVE RESISTANCE OF THE COLUMN SUBJECT TO AXIAL LOAD

One of the main problems in columns is their tendency to buckle. Only short columns can be easily designed using formula for compressive resistance based on gross cross section and yield strength. The main problem of the compression member is its tendency to buckle before it yields even if the column is straight, homogenous, and centrally loaded. This phenomenon was described in mathematical terms by Leonhard Euler in 1759 [3]. The elastic critical load or buckling load of an axially compressed straight column is given by Euler theory as [3]:

$$P_E = \pi^2 EI/L^2 \tag{1}$$

where I = second moment of area of the section
E = elastic modulus of steel (205 kN/mm^2)
L = length of the column (or distance between restraints)

In case of cruciform column, the second moment of area, I is greater than the typical universal column section which will increase the value of load, P_E. Writing this in terms of stress p_E by dividing the cross-sectional area A, and defining the radius of gyration r as $I = Ar^2$, gives

$$p_E = \pi^2 E\,(Ar^2)/(L^2 A) = \pi^2 E/(L/r)^2 = \pi^2 E/\lambda^2 \tag{2}$$

The controlling parameter is therefore, λ, the slenderness ratio (L/r) of the column, with the elastic critical stress p_E being inversely proportional to the square of the column slenderness. It follows that there is a certain slenderness λ_1 at which theoretically, $p_E = p_y$, the design strength of steel. This is given by $\lambda_1 = \pi\sqrt{E/p_y}$. Columns usually have different second moments of area in different directions (e.g. $I_{x\text{-}x}$ and $I_{y\text{-}y}$ sections). Therefore, radius of gyration r_x and r_y may be defined as relevant values in the directions, parallel and perpendicular to the web (usually the major and minor stiffness directions) respectively. However, for cruciform column, the $I_{x\text{-}x}$ and $I_{y\text{-}y}$ sections are equal which also result in the same stiffness in the major and minor axis. According to Euler theory, lateral torsional buckling will occur in the $y - y$ direction if $r_y < r_x$, unless lateral movement is restrained in this direction. However, this problem will not occur in the cruciform column, as the axes are symmetrical. The presence of an initial lack of straightness and/or small eccentricities of loading will mean that the column of struts will develop lateral deformations gradually rather than as a sudden process. Thus, yielding will develop from the more heavily compressed regions, leading to a progressive loss of stiffness. Since the actual magnitude and distribution of factors like initial deformation and residual compressive stress will vary both between section types and, to some extent, within different samples of the same section, the actual relationship between column strength and slenderness will spread over a relatively wide range.

BS 5950 Part 1: 2000 [4] recognizes this by providing four column curves, (see Figure 2), each of which is represented by a modified Perry-Robertson formula as follows [3]:

$$(p_E - p_C)\ (p_y - p_C) = \eta p_E p_C \tag{3}$$

where p_C = compressive strength of column (to be determined)
p_y = design strength of steel
η = $0.001\alpha\,(\lambda - \lambda_0)$
λ_0 = $0.2\lambda_1$

By solving Equation (3), the value of p_c may be obtained using:

$$p_C = p_E p_y / (\emptyset + (\emptyset^2 - p_E p_y)^{1/2}) \tag{4}$$

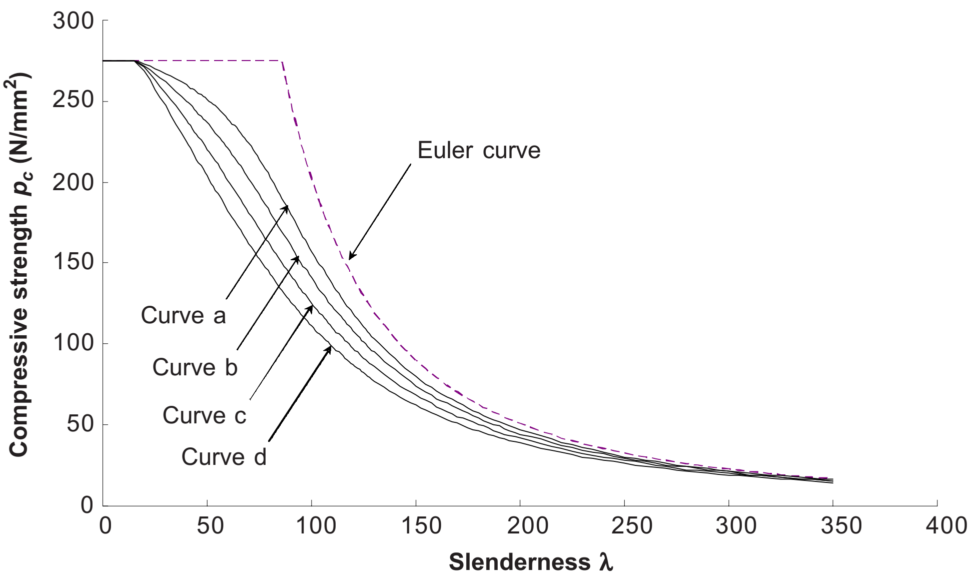


Figure 2 Compressive strength curves of BS 5950: Part 1, $p_y = 275\text{N/mm}^2$

In which $\text{Ø} = (P_y + (\eta + 1)\, p_E)\,/2$

$p_E = \pi^2 E/\lambda^2$

where λ is the slenderness ratio (L/r).

From the expression for the Perry coefficient, it follows that $p_C = p_y$ when $\lambda = \lambda_0$, which represents the limiting slenderness of a stocky column.

The original Perry formula (without λ_0) is based on "first yield" of a point on the cross-section of the column. The Perry coefficient η is an initial imperfection parameter dependent on the type of section, and the method of forming (i.e. rolling or welding), which is a function of the slenderness of the column. The values of the "Robertson constant" α have been determined from tests [3] which allow for actual failure (not necessarily first yield). Positioning of four design curves (a to d) is controlled by selecting four different values for the Robertson constant α (2.0, 3.5, 5.5, 8.0) depending on the types of cross section, type of axis, and thickness of the flange.

For cruciform column, the Robertson constant of 2.0 is assumed as the same value used for universal beam sections in major axis [3]. This value applied for both axes of the cruciform column where no flange is greater than 40 mm thick. The reason for using 2.0 as Robertson constant is that the formation of cruciform column is by the use of universal beam and the bending on major axis in universal beam is stronger than the minor axis. Therefore, the assumption of using 2.0 as the constant for cruciform column is consistent with the constant suggested by BS 5950.

3.1 Compressive Resistance

The compression resistance of members is determined by three properties namely material strength, section classification, and member slenderness [4]. In the code of practice [4], the compression resistance is expressed in terms of a compressive strength, which takes into account both material strength and member slenderness, and a cross-sectional area that depends on the cross section classification. The compression resistance is given by:

For non-slender cross-sections (Class1, 2 or 3) $P_c = A_g \times p_c$
For Class 4 slender cross-sections $P_c = A_{eff} \times p_{cs}$

where A_g = gross area of the section
A_{eff} = effective area of the section
p_c = compressive strength for a non-slender section
p_{cs} = compressive strength for a slender section

The classification of cruciform columns does not fall into the slender category as the depth between fillets has been reduced into half and will reduce the ratio of depth between fillet and the thickness of the web. Therefore, the compression resistance is calculated as $P_c = A_g p_c$.

3.2 Slenderness

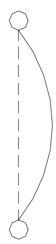
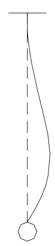
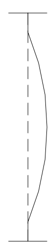
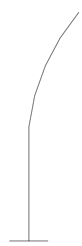
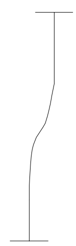
The resistance of a member to overall buckling depends on the slenderness of the section. The slenderness for non-slender cross-sections (Class 1, 2 or 3) is given by $\lambda = L_E/r$

where L_E = effective length,
r = radius of gyration, for the relevant axis of buckling where in cruciform column the both axes are the same.

3.3 Effective Length

The effective length of a compression member is a function of the actual length between restraints and the type of restraint provided. The restraint of the column is usually associated with the type of connection used at the end of the column. The restraint at the ends of the column will affect the buckling shape of the column (see Table 1) which therefore, affects the compressive resistance of the column. In Table 1, rigid joint results in shorter effective length. The smaller the effective length, the higher will be the compressive resistance of the column. The effective length of columns also depends on whether the frame is braced or unbraced. For unbraced frame, the effective length is greater than the braced frame due to the sway behavior of the frame. For

Table 1 Deformation shape with end restraint condition L_E [2]

		Braced frame			**Unbraced frame**
Restraint at	Position only (pinned joint)	Position and direction (fixed joint)	Position and direction (fixed joint)	None	Direction only
Buckled shape					
Restraint at end 2	Position and (pinned joint)	Position and (fixed joint)	Position and direction (fixed joint)	Position and direction (fixed joint)	Position and direction (fixed joint)
Practical L_E	1.0 L	0.85 L	0.7 L	2.0 L	1.2 L

braced frames, the effective length is equal to 1.0 L or less depending on the condition of end restraints. For end restraint with pinned joint, the effective length is taken as 1.0 L while for fixed joint, the effective length is taken as 0.7 L to 0.85 L as shown in Table 1. The length (L) used in Table 1 is the distance of the member between two restraints.

4.0 COLUMN CAPACITY

The column capacity for cruciform section can be calculated from the Perry-Robertson formula in Equation (4). In accordance to BS 5950: Part 1, sections which have lower compression resistance are designed using one of the lower curves. As for the cruciform column, the formation is based on a combination of two universal beams. This combination will give rise to stiffer member compared to a single universal beam and universal column as a column. Therefore, the constant used in the Perry-Robertson is taken as 2.0, which is the upper bound value for the calculation of compression resistance of columns. The actual process of design, therefore, consists of the following steps:

(i) Select trial section.
(ii) Determine effective length of column, L_E, in x and y directions.
(iii) Calculate $\lambda = L_E/r$.
(iv) Obtain the value of p_c for each direction as a function of λ and p_y and select the lower value.
(v) Compare $P_c = A_g p_c$ with the factored applied axial load for the design of compression member.

Since this is a "trial" method, therefore, to utilise the use of cruciform column in the design, tables of compression capacity are produced (please refer to Tables 2(a to d)). These tables consist of the compression capacity for cruciform column with steel grade S275 fully stressed by axial load only for different effective lengths. With these tables, the design for axially loaded column can be easily done by just comparing the required compression capacity of a cruciform section that has been established in the tables.

4.1 Discussions on the Compression Capacity Tables

The compression capacity tables are best presented by listing the size of the beam used together with the effective length of the column as shown in Tables 2(a) to 2(d). The values given are calculated based on the design strength of S 275 steel grade with the effective lengths ranging from 2.0 to 14.0 m, for the size of beam ranging from Cruciform Column Universal Beam(hereafter referred to as CCUB) 1016 × 305 × 974 to CCUB 610 × 305 × 149. For smaller beams with size ranging from CCUB 610 × 229 × 140 to CCUB 127 × 76 × 13, the effective lengths are ranged from 1.0 to 7.0 m. From the tables, the results show that the compression capacity of the CCUB is constant at a

Table 2(a) Compression capacity for cruciform column for steel grade S 275

Section designation	Compression resistance in kilonewtons for effective length in metres												
	2.0	**3.0**	**4.0**	**5.0**	**6.0**	**7.0**	**8.0**	**9.0**	**10.0**	**11.0**	**12.0**	**13.0**	**14.0**
1016×305×974	31620	31620	31620	31620	31432	31198	30956	30704	30439	30159	29860	29538	29191
1016×305×874	28407	28407	28407	28407	28233	28022	27804	27577	27337	27084	26814	26523	26208
1016×305×786	25500	25500	25500	25500	25338	25147	24950	24744	24527	24298	24052	23788	23502
1016×305×698	23585	23585	23585	23585	23421	23244	23061	22870	22668	22453	22223	21975	21705
1016×305×628	21200	21200	21200	21200	21048	20888	20723	20550	20367	20172	19964	19738	19493
1016×305×544	18391	18391	18391	18391	18256	18116	17972	17821	17661	17492	17309	17112	16897
1016×305×498	16801	16801	16801	16785	16658	16526	16390	16247	16095	15933	15758	15568	15360
1016×305×444	14999	14999	14999	14970	14853	14732	14606	14473	14331	14180	14015	13836	13639
914×419×776	26182	26182	26182	26155	25956	25751	25538	25314	25077	24823	24550	24253	23928
914×419×686	23161	23161	23161	23130	22952	22769	22578	22377	22164	21936	21690	21423	21129
914×305×578	19504	19504	19504	19449	19293	19132	18963	18784	18594	18388	18165	17921	17652
914×305×506	17119	17119	17119	17066	16928	16785	16635	16476	16307	16125	15926	15708	15468
914×305×448	15158	15158	15158	15103	14979	14850	14715	14571	14418	14253	14072	13873	13653
914×305×402	13568	13568	13568	13509	13395	13277	13153	13021	12880	12726	12559	12373	12168
838×292×453	15317	15317	15317	15227	15092	14953	14805	14647	14477	14291	14086	13858	13604
838×292×388	13091	13091	13091	13002	12885	12762	12632	12493	12342	12177	11994	11790	11560
838×292×352	11872	11872	11872	11784	11675	11562	11441	11312	11171	11017	10845	10653	10437
762×267×394	13303	13303	13289	13162	13030	12890	12740	12577	12398	12197	11972	11717	11426
762×267×346	11660	11660	11642	11529	11411	11287	11153	11007	10845	10665	10462	10230	9967
762×267×294	9911	9911	9889	9791	9688	9580	9463	9334	9192	9032	8852	8646	8410
762×267×268	9405	9405	9373	9279	9180	9074	8959	8832	8691	8531	8348	8138	7897
686×254×340	11501	11501	11445	11322	11192	11053	10901	10733	10543	10327	10079	9792	9464
686×254×304	10282	10282	10229	10118	10001	9876	9739	9586	9414	9218	8992	8732	8433
686×254×280	9434	9434	9383	9280	9172	9056	8929	8787	8627	8444	8233	7990	7711
686×254×250	8427	8427	8375	8282	8183	8077	7960	7829	7681	7511	7315	7087	6826
610×305×476	16059	16059	15949	15767	15575	15366	15136	14878	14584	14246	13854	13400	12878
610×305×358	12084	12084	11993	11854	11705	11545	11367	11166	10937	10673	10365	10008	9598
610×305×298	10070	10070	9991	9874	9749	9614	9464	9295	9101	8876	8615	8312	7965

Table 2(b) Compression capacity for cruciform column for steel grade S 275

Section designation	Compression resistance in kilonewtons for effective length in metres												
	1.0	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**	**6.5**	**7.0**
610×229×280	9434	9434	9434	9434	9434	9397	9341	9284	9226	9165	9102	9035	8965
610×229×250	8427	8427	8427	8427	8427	8391	8341	8290	8237	8183	8125	8066	8003
610×229×226	7632	7632	7632	7632	7632	7596	7550	7503	7455	7404	7352	7296	7238
610×229×202	7095	7095	7095	7095	7095	7052	7008	6963	6917	6868	6818	6764	6707
533×210×244	8215	8215	8215	8215	8193	8139	8083	8025	7965	7902	7835	7764	7688
533×210×218	7367	7367	7367	7367	7344	7295	7244	7192	7137	7079	7018	6953	6884
533×210×202	6837	6837	6837	6837	6815	6769	6722	6672	6621	6567	6510	6450	6385
533×210×184	6435	6435	6435	6435	6409	6365	6320	6273	6224	6172	6117	6058	5995
533×210×166	5775	5775	5775	5775	5746	5706	5664	5621	5576	5528	5476	5421	5362
457×191×196	6625	6625	6625	6617	6567	6515	6461	6404	6343	6279	6209	6133	6051
457×191×178	6042	6042	6042	6033	5987	5939	5889	5836	5780	5721	5656	5586	5509
457×191×164	5720	5720	5720	5707	5662	5616	5568	5518	5464	5405	5342	5273	5197
457×191×148	5203	5203	5203	5190	5149	5107	5063	5016	4967	4913	4855	4792	4722
457×191×134	4703	4703	4703	4688	4651	4612	4572	4529	4483	4434	4380	4321	4255
457×152×164	5565	5565	5565	5551	5507	5462	5414	5364	5310	5253	5190	5122	5047
457×152×148	5009	5009	5009	4995	4956	4914	4871	4826	4777	4725	4668	4606	4538
457×152×134	4708	4708	4708	4690	4652	4613	4571	4527	4480	4429	4373	4312	4244
457×152×120	4191	4191	4191	4175	4140	4105	4068	4028	3986	3940	3890	3835	3773
457×152×104	3663	3663	3663	3645	3615	3583	3549	3514	3475	3434	3388	3337	3280

Table 2(c) Compression capacity for cruciform column for steel grade S 275

Section designation	Compression resistance in kilonewtons for effective length in metres												
	1.0	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**	**6.5**	**7.0**
406×178×148	5198	5198	5198	5164	5118	5071	5020	4966	4908	4844	4773	4694	4605
406×178×134	4703	4703	4703	4670	4629	4585	4539	4490	4436	4377	4312	4239	4156
406×178×120	4208	4208	4208	4178	4141	4102	4060	4015	3967	3914	3855	3789	3714
406×178×108	3795	3795	3795	3765	3730	3694	3655	3614	3568	3518	3463	3400	3329
406×140×92	3223	3223	3223	3195	3165	3134	3100	3064	3024	2980	2931	2875	2813
406×140×78	2734	2734	2731	2706	2679	2651	2622	2589	2553	2513	2468	2417	2359
356×171×134	4703	4703	4693	4648	4600	4550	4495	4436	4370	4296	4213	4117	4008
356×171×114	3993	3993	3983	3943	3902	3859	3811	3759	3702	3637	3563	3478	3381
356×171×102	3570	3570	3559	3524	3487	3447	3404	3357	3305	3246	3179	3102	3013
356×171×90	3152	3152	3140	3108	3075	3039	3000	2957	2909	2855	2793	2721	2639
356×127×78	2739	2739	2726	2697	2667	2634	2599	2559	2514	2464	2405	2337	2260
356×127×66	2316	2316	2302	2277	2251	2223	2191	2156	2117	2072	2019	1959	1889
305×165×96	3784	3784	3755	3712	3666	3616	3561	3499	3427	3345	3248	3136	3007
305×165×84	3229	3229	3203	3166	3127	3084	3037	2983	2921	2850	2767	2670	2558
305×165×74	2822	2822	2798	2766	2731	2693	2651	2603	2548	2484	2409	2322	2222
305×127×96	3366	3366	3331	3289	3245	3196	3140	3077	3003	2916	2814	2695	2560
305×127×84	2937	2937	2905	2868	2829	2785	2736	2680	2613	2536	2444	2337	2216
305×127×74	2596	2596	2567	2534	2499	2460	2416	2366	2307	2237	2155	2059	1951

Table 2(d) Compression capacity for cruciform column for steel grade S 275

Section designation	Compression resistance in kilonewtons for effective length in metres												
	1.0	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**	**6.5**	**7.0**
305×102×66	2299	2299	2274	2245	2214	2180	2141	2097	2045	1983	1911	1827	1732
305×102×56	1975	1975	1951	1925	1898	1868	1833	1793	1746	1690	1625	1549	1463
305×102×50	1738	1736	1715	1691	1666	1638	1605	1568	1523	1470	1407	1334	1254
254×146×86	3014	3006	2966	2923	2876	2822	2760	2686	2598	2493	2368	2227	2073
254×146×74	2596	2588	2553	2516	2474	2427	2373	2308	2230	2137	2027	1903	1769
254×146×62	2184	2174	2144	2111	2075	2033	1984	1926	1855	1770	1671	1560	1442
254×102×57	1986	1975	1946	1916	1881	1841	1793	1736	1667	1584	1487	1380	1269
254×102×50	1760	1749	1723	1695	1663	1626	1582	1529	1464	1386	1296	1198	1098
254×102×44	1540	1529	1505	1480	1451	1416	1375	1325	1264	1191	1107	1018	929
203×133×60	2101	2075	2039	1998	1949	1890	1817	1726	1614	1486	1350	1217	1092
203×133×50	1760	1737	1706	1670	1628	1576	1512	1431	1333	1222	1106	993	889
203×102×46	1617	1593	1563	1528	1486	1435	1369	1288	1189	1081	971	867	773
178×102×38	1334	1308	1278	1243	1199	1141	1067	975	874	773	681	599	528
152×89×32	1108	1081	1049	1009	955	882	790	691	597	514	445	387	338
127×76×26	892	865	829	778	706	615	520	435	366	310	265	228	199

certain effective length of the column. This is because the slenderness ratio of the CCUB sections at certain length is less or equal to the λ_0 so that the compressive strength p_c is equal to p_y. The compression capacities values are then gradually reduced in a non-linear manner in accordance with the predicted graph as shown in Figure 2. The compression capacity decreases as the effective length increases. The reduction of the compression capacity is not drastically reduced, as the stiffness of the cruciform column is higher than the UB or the UC sections. As the effective length increases, the slenderness ratio of the column increases and the overall buckling effect (lateral deformations) started to control the compression capacity.

5.0 COMPARISON BETWEEN CCUB, UB AND UC SECTIONS

To investigate the effectiveness of cruciform column, a comparison was made between cruciform column, UB and UC sections for the compression capacities ranging from 3000 to 5000 kN. The compression capacities for different hot-rolled sections with cruciform columns under various load case with various effective lengths have been studied in order to compare the effectiveness in percentage of weight savings. The results of the calculation are summarized in Tables 3(a) to 3(c). The purpose of the case study is to test the capacity of different sections to determine which section will contribute less self weight. From the tables, the use of CCUB sections have reduced the steel weight by up to 35.44% as compared with UC sections and up to 59.68% as compared with UB sections. These results show that the use of CCUB section has significantly increased the compression capacity of the column with the same mass of steel. The results also show that the percentage saving in steel starts to be reduced as the required axial load increases. This is probably due to the size of UB and UC which gets larger and stiffer than the size of column designed for lesser load capacity.

Table 3(a) Comparison between UB, UC, and CCUB under an axial load of 3000 kN with an effective length of 6 meter

Section	Dimension	P_{cx} kN	P_{cy} kN	Mass per meter kg/m	Length m	Self-weight kg	Percentage of steel weight difference compare to CCUB
Cruciform column	356 × 171 × 102	3388	3388	102	6	612	–
Universal column (UC)	305 × 305 × 158	4780	3320	158	6	948	35.44
Universal beam (UB)	914 × 305 × 253	5950	3890	253	6	1518	59.68

Table 3(b) Comparison between UB, UC, and CCUB under an axial load of 4000 kN with an effective length of 6 meter

Section	Dimension	P_{cx} kN	P_{cy} kN	Mass per meter kg/m	Length m	Self-weight kg	Percentage of steel weight difference compared to CCUB
Cruciform column	356 × 171 × 134	4213	4213	134.2	6	805.2	–
Universal column (UC)	305 × 305 × 198	6030	4220	198	6	1188	32.22
Universal beam (UB)	914 × 305 × 289	8620	5250	289	6	1734	53.56

Table 3(c) Comparison between UB, UC, and CCUB under an axial load of 5000 kN and an effective length of 6 meter

Section	Dimension	P_{cx} kN	P_{cy} kN	Mass per meter kg/m	Length m	Self-weight kg	Percentage of steel weight difference compared to CCUB
Cruciform column	457 × 152 × 164	5190	5190	164.2	6	985.2	–
Universal column (UC)	305 × 305 × 240	7330	5180	240	6	1440	31.58
Universal beam (UB)	610 × 305 × 238	7950	5190	238	6	1428	31.01

6.0 COMPARISON OF MAXIMUM COMPRESSION CAPACITY WITH DIFFERENT EFFECTIVE LENGTHS

For the second stage of comparison, the maximum compression capacity of each hot-rolled section was considered. This comparison was done by taking into account the maximum compression capacity of the biggest section available in the market. The purpose of this comparison is to find out which section is able to sustain the largest axial load. The result of the comparison is summarised in Table 4. To have a better understanding of the effect of using CCUB sections, the comparison is also illustrated in Figure 3. The results show that cruciform columns has the highest maximum capacity which is almost two times the capacity of the largest available circular hollow sections (CHS) and three times the capacity of the largest available UC sections in the market.

Table 4 Compression capacities (in kN) of various hot-rolled sections with different effective length

Section type	Effective length												
	2.0 m	**3.0 m**	**4.0 m**	**5.0 m**	**6.0 m**	**7.0 m**	**8 m**	**9 m**	**10 m**	**11 m**	**12 m**	**13 m**	**14 m**
CCUB (1016×305×487)	31620	31620	31620	31620	31432	31198	30956	30704	30439	30159	29860	29538	29191
Circular hollow section (500×300×20.0)	24400	24400	24400	24200	23900	23600	23400	23100	22700	22300	21900	21400	20900
Square hollow section (400×400×20)	22700	22700	22600	22400	22200	22000	21700	21500	21200	20800	20500	20000	19600
Rectangular hollow section (500×300×20)	7940	7820	7670	7490	7280	7020	6690	6280	5790	5260	4720	4210	3750
Universal column (UC356×406×634)	19800	18300	16900	15600	14200	12900	11700	10500	9410	8440	7580	6820	6150
Universal beam (UB1016×305×487)	12900	12400	11800	11200	10300	9420	8410	7400	6470	5640	4930	4330	3820

This result shows that the cruciform column is one of the best alternative sections available to be used in the design of column for high-rise building where heavy compression load is needed as the largest size of UC and CHS have limited compression capacity as shown in Figure 3. The symmetrical axis for the cruciform column will enhance the compression resistance and the fabrication of the beam-to column connection which results in added advantages compared with other sections.

7.0 CONCLUSION

Conclusions of the study on compression capacity of cruciform column under axial load are as follows:-

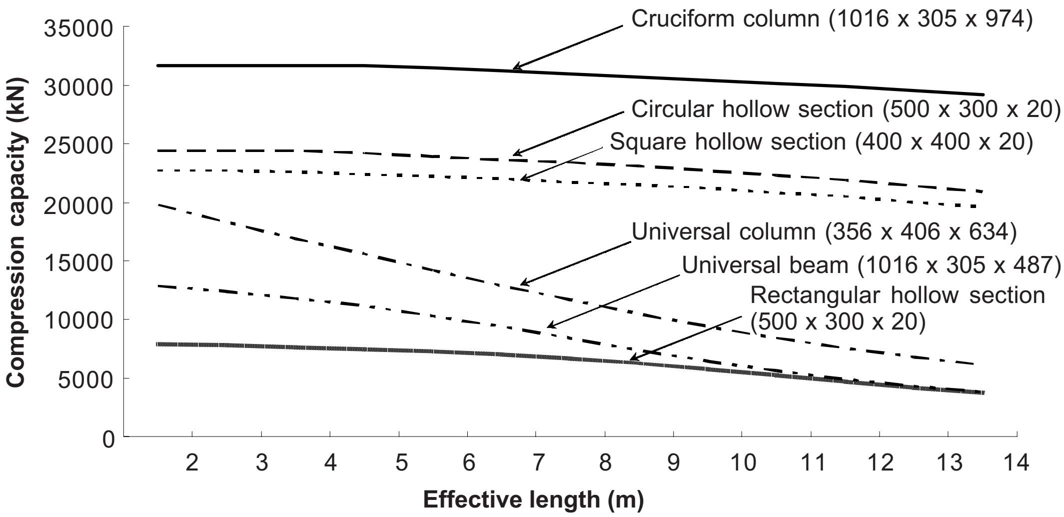


Figure 3 Graph of compression capacities versus effective length

(i) The development of cruciform column by using universal beam section increases the cross sectional area and second moment of inertia of CCUB section which resulted in an increase in the compression capacity.

(ii) The establishment of compression capacity tables for cruciform universal beam column is possible by adopting the methods described in BS 5950:2000 Part 1 [4] and the design guide in Steel Construction Institute [5].

(iii) The percentage saving in steel weight by using cruciform universal beam sections as column is up to 35.44% as compared with UC section and 59.68% as compared with UB section.

(iv) The maximum compression capacity of cruciform universal beam section as column can provide almost three times the maximum compression capacity of other conventional compression members.

(v) The use of cruciform columns will enhance the design aspects of multistorey steel frames by providing symmetrical axis where the compression capacity on x-x and y-y axis has the same value.

(vi) Easy to fabricate the beam-to-column connection as lack of fit which occurs on minor axis connection can be avoided.

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REFERENCES

[1] Nethercot, D. A. 1991. *Limit States Design of Structural Steelwork*. Second edition. Nottingham: Chapman & Hall.

[2] Way, A. G. J., and P. R. Salter. 2003. *Introduction to Steelwork Design to BS 5950-1:2000*. Berkshire: The Steel Construction Institute.

[3] Nethercot, D. A., and R. M. Lawson. 1992. *Lateral Stability of Steel Beams and Columns – Common Cases of Restrain*. Berkshire: The Steel Construction Institute.

[4] British Standard Institute. 2000. *BS 5950: Structural Use of Steelwork in Building Part 1: Code of Practice for Design Rol led and Welded Sections*. London: British Standards Institution.

[5] The Steel Construction Institute and the British Constructional Steelwork Association Limited. 2002. *Steelwork Design Guide to BS 5950: Part 1: 2000 Volume 1 Section Properties Member Capacities (6th Edition) Incorporating Amendment 1 (June 2002)*. London.

[6] Trahair, N. S., M. A. Bradford, and D. A. Nethercot. 2001. *The Behaviour and Design of Steel Structures to BS 5950*. Third Edition-British. London: Spon Press.

[7] You, C. K., T. Hidetoshi, N. Eiji, and H. Kohsuke. 1999. Buckling Characteristics of High Manganese Non-magnetic Steel and Carbon Steel Hybrid Cruciform Columns. *Trans. JWRI*. 28.

[8] Nicos, M. 2003. Plastic Torsional Buckling of Cruciform Compression Members. *Journal of Engineering Mechanics© ASCE*. 129.

[9] Burl, E. D. 2002. Universal Column Formula. Practice Periodical on Structural Design and Construction© ASCE. 7.

[10] Saleh, H. A., and B. Reidar. 1989. Inelastic Behavior of Single Angle Columns. *Journal of Construction Steel Research*. 12: 103-118.