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Research Article

Effect of hollow concrete sections on moment capacity of circular concrete-filled steel tube beams under pure bending

Khanh Ba Le[1,2], Vui Van Cao[1,2,*]

ABSTRACT

Compared with reinforced concrete, concrete filled steel tube (CFST) has several advantages due to the mutually beneficial interaction between steel tube and concrete. A large number of studies of CFST columns have been performed, whereas those of CFST beams appear to be limited in the literature. Therefore, studies on CFST beams should be encouraged for building beam-column frame structures. When a concrete filled steel tube (CFST) beam is subjected to a bending moment, its sections are divided into compression and tension zones. An area of concrete near the neutral axis may participate limitedly in the resistance of CFST sections; thus, it can be made hollow to reduce the self-weight and cost. This paper thus investigates the effect of hollow concrete sections on the moment capacity of CFST beams. A CFST section was selected, and its fiber model was developed and verified. After that, a total of 60 sections of three diameter-to-thickness (*D/t*) ratios of 40.64, 53.5, and 78.2 were analysed and compared. The effect of hollow concrete sections was analysed and led to the conclusions. The results indicate that the moment–curvature curves are moderately affected by the hollow concrete sections. The results also showed that the concrete area can be made void up to 30.25% of the total area of CFST sections. The void area can be slightly increased up to 42.25% as the *D/t* ratio increased. The results also indicated that the concrete infill contributed 15.4%–19.8% to the capacity of CFST sections. The contribution of concrete infill to the moment capacity of CFST sections slightly increased as the *D/t* ratio increased. These outcomes can be useful information for structural engineers when designing circular CFST beams with hollow sections.

Key words: Moment capacity, Concrete filled steel tube (CFST), Beam, Hollow section, Bending

[1]*Faculty of Civil Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam*

[2]*Vietnam National University Ho Chi Minh City (VNU-HCM), Linh Trung Ward, Thu Duc City, Ho Chi Minh City, Vietnam*

Correspondence

Vui Van Cao, Faculty of Civil Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam

Vietnam National University Ho Chi Minh City (VNU-HCM), Linh Trung Ward, Thu Duc City, Ho Chi Minh City, Vietnam

Email: cvvui@hcmut.edu.vn

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INTRODUCTION

Due to the mutual benefits of the interaction between steel tube and concrete, concrete filled steel tube (CFST) owns several advantages when compared with reinforced concrete (RC). CFST does not need formwork during its construction, while concrete spalling is prevented by steel tubes. Different aspects of CFST, such as failure pattern [1], load-carrying capacity and ductility [2,3], behaviour [4,5], and absorbed energy [6,7], have been investigated.

A large number of investigations of CFST columns have been performed, whereas those of CFST beams appear to be limited, as raised by researchers [8,9]. This is due to the interesting confinement effect in CFST columns. In contrast, the confinement effect in CFST beams is limited, but CFST beams are obviously better than steel tube (ST) beams. Lu and Kennedy [10] experimentally investigated the flexural behaviour of rectangular and square ST and CFST beams and found that the steel ratio controlled the increase in the ultimate strength of CFST beams compared to that of ST beams. They established models to calculate the flexural capacity of CFST beams. Elchalakani et al. [8] experimentally studied the behaviour of circular ST and CFST beams under pure bending, and concluded that the infill concrete enhanced the strength and ductility of CFST beams. Han [11] developed models to predict the flexural behaviour of rectangular and square CFST beams, and these models were used by Han et al. [12] to investigate the flexural performance of CFST beams made of self-consolidating concrete. Lu et al. [13] confirmed that the behaviour of circular CFST beams was negligibly influenced by the ratio of shear span to beam depth. Chitawadagi and Narasimhan [14] investigated the effect of concrete strength on the flexural behaviour of circular CFST beams and found that the concrete strength slightly changed the capacity of the CFST beams. Moon et al. [15] found that local buckling was delayed and the load-carrying capacity of CFST beams increased when the ratio of steel strength to concrete strength increased. Jiang et al. [16] confirmed the high ductility of CFST beams. Lai et al. [17] tested nine high-strength square CFST members under cyclic loadings and found that local buckling and steel rupture were the failure modes.

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With high-strength steel, CFST members had a higher load-carrying capacity but lower ductility, while stiffness was negligibly affected. Gunawardena et al. [18] reviewed and studied the moment capacity of circular CFSTs under bending. 219 test results of circular CFSTs collected from the literature were used for reliability analyses. The results confirmed the adequate reliability level of AS/NZS 2327 [19] for design. Zarringol et al. [20] studied the design calculations of different design standards applied for rectangular CFST beam-columns with slender sections under combinations of axial compression and bending. Modifications were proposed to improve the design procedures. Xie et al. [21] tested 14 circular and square CFST beams made of normal and recycled concrete and different corrosion levels. They found that the corrosion noticeably decreased the ultimate load-carrying capacity and caused more apparent local buckling of CFST beams. Investigations on CFST beams under combined and cyclic loadings have also been conducted by researchers [22–24].

The above review indicates that the literature focuses on CFST beams with full infill concrete, while CFST beams with hollow sections seem to be hardly found in the literature. Under bending moments, the infill concrete near the neutral axis participates limitedly in the resistance of CFST beams. Therefore, it can be partly removed to reduce the self-weight and save on cost. This study aimed in this direction to provide information for engineers in practice. To achieve this aim, a circular section analysed by Liew and Xiong [25] was selected. A model of this CFST section was developed in SAP2000 [26], and it was verified by comparing its result with the result of an available theoretical model. After verification, the model was developed for various CFST sections with consideration of hollow concrete sections. The results were analysed and compared to clarify the effect of hollow concrete sections on moment capacity of CFST sections. The comparison results were used to draw conclusions, which can be beneficial to structural engineers when designing hollow CFST beams.

DESCRIPTIONS OF CIRCULAR CFST BEAM SECTIONS

The circular section analysed by Liew and Xiong [25] was revisited. The outer diameter was 508 mm, and the thickness of the steel tube was 12.5 mm. The compressive strength of concrete was 40 MPa. The steel was S355, with a yield strength of 355 MPa. The ultimate strain ε_u was taken as 0.025 [27]. The elastic modulus was $E_s = 2 \times 10^5$ MPa. The elasto-plastic model of steel adopted in ACI 318-19 [28] and the stress-strain model proposed by Hognestad [29] were selected to be used in this paper. These stress-strain models of steel and concrete are shown in Figure 1a and b, respectively.

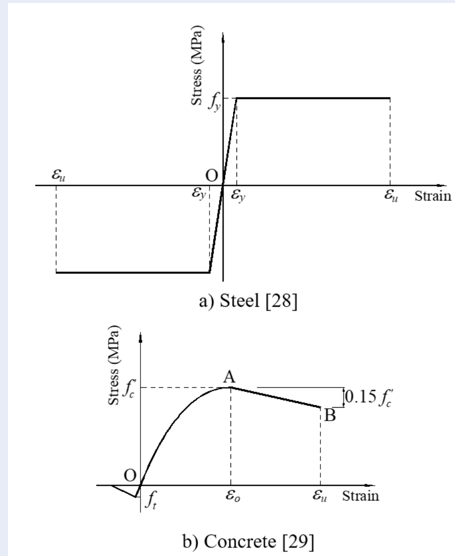

Figure 1: Models of steel and concrete.

METHOD

CFST sections can be considered composite sections regardless of the imperfection of the connection between the steel tube and concrete. The composite concept was employed by Han [11] to develop a model of moment capacity for CSFT sections. Using this concept, Han [11] transformed CFST sections into composite sections. Then, the bending formula of the mechanics of materials was applied and modified using a regression factor. The Han [11] model is shown in Equation 1, where M_u is the moment capacity; W_{scm} is the section modulus of the rectangular CFST beams (Equation 2); f_{scy} is the "nominal yield strength" of composite sections [30], which is determined by Equation 3; and γ_m is termed the flexural strength index (Equation 4), which was determined based on regression analysis using the experimental data. In Equations 3 and 4, ξ is the confinement factor; f_{ck} is the characteristic strength of concrete, which equals the compressive strength of cylinder concrete samples [31].

$Mu = \gamma_m W_{scm} f_{scy}$ (1)

$W_{scm} = (\pi \times D^3)/32$ for circular sections (2)

$f_{scy} = (1.14+1.02\xi) f_{ck}$ (3)

$\gamma_m = 1.1 + 0.48\ln(\xi + 0.1)$ (4)

For the CFST section described in Section 2, the parameters are determined as A_s = 19458.2 mm^2, A_c = 183224.8 mm^2, W_{csm} = 12870370 mm^2, ξ = 0.943, f_{scy} = 84.055 MPa, γ_m = 1.12. Consequently, the ultimate moment is M_u = 1211.6 kNm based on Han [11] model.

The above CFST section was modeled in SAP2000 [26] using the information in Section 2. Figure 2 shows the model of the CFST section in SAP2000 section designer [26]. Figure 3 shows the moment–curvature curves obtained from the fiber-modeled analysis. The ultimate moment was 1258.7 kNm. Compared with the ultimate moment M_u = 1211.6 kNm obtained from Han [11] model, the difference is 3.9%, showing a good agreement between the two results.

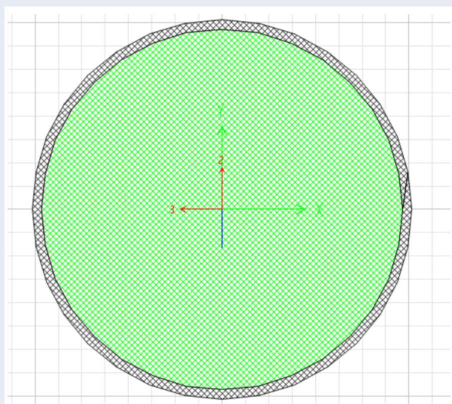

Figure 2: CFST section in SAP2000 section designer [26].

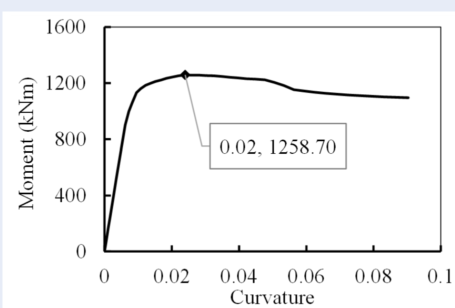

Figure 3: Moment–curvature curves of the CFST section

RESULTS AND DISCUSSIONS OF MOMENT CAPACITY OF CFST BEAM SECTIONS

Figure 4 shows a typical CFST section with hollow sections. In this section, CFST sections with different *D/t* and *d/D* ratios were used for analyses. The CFST section with the outer diameter of *D* = 508 mm described in Section 2 was modified. The steel thicknesses were selected to be 12.5, 9.5, and 6.5 mm, which made *D/t* ratios of 40.64, 53.5, and 78.2, respectively. CFSTs without and with hollow sections were analysed. The hollow diameters *d* were selected based on the *d/D* ratio varying from 0 to its maximum value. The maximum value of *d/D* corresponds to the steel tube section. The increment of the *d/D* ratio was selected to be 0.05. Table 1 shows different CFST sections with a constant outer diameter of *D* = 508 mm, while values of *d/D* ratio and *d* vary as presented in columns 2 and 3, respectively. The last row of Table 1 shows the steel sections, in which the ratio of *d/D* was calculated.

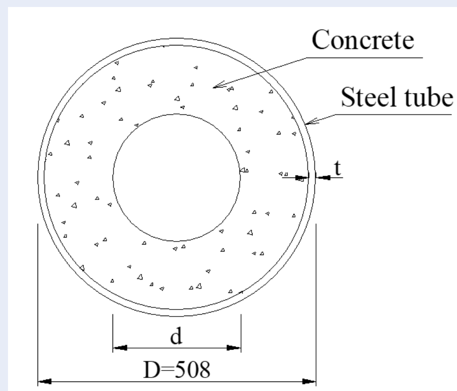

Figure 4: CFST with hollow sections

A total of 60 analyses were performed for three *D/t* ratios and 20 sections for each *D/t* ratio. Figure 5a shows 20 moment-curvature curves of CFST sections with a *D/t* of 40.64 but different hollow sections. Similarly, Figure 5b and c show the moment–curvature curves of CFST sections with *D/t* of 53.5 and 78.2, respectively. The highest curve is of the CFST section without a hollow section. The lowest curve is of the ST section (CFST section with a *d/D* of 0.95-0.97). This figure indicates that the contribution of the infill concrete to the moment capacity is moderate. The moment capacity of CFST beam sections is governed by the steel tubes.

Table 1: Hollow CFST sections.

No.	d/D ratio	d (mm)	Percentage of hollow area to whole area (%)
1	0	0.0	0
2	0.05	25.4	0.25
3	0.10	50.8	1.00
4	0.15	76.2	2.25
5	0.20	101.6	4.00
6	0.25	127.0	6.25
7	0.30	152.4	9.00
8	0.35	177.8	12.25
9	0.40	203.2	16.00
10	0.45	228.6	20.25
11	0.50	254.0	25.00
12	0.55	279.4	30.25
13	0.60	304.8	36.00
14	0.65	330.2	42.25
15	0.70	355.6	49.00
16	0.75	381.0	56.25
17	0.80	406.4	64.00
18	0.85	431.8	72.25
19	0.90	457.2	81.00
20	0.95 (0.96 and 0.97)	483 (489 and 495)	90.4 (92.7 and 94.95)

Figure 6a shows the variations in the ultimate moment of CFST sections with a *D/t* of 40.64 with respect to different *d/D* ratios. This figure shows the following interesting aspects. The moment capacity is almost unchanged when the *d/D* ratio varies from 0.0 to 0.50. This indicates that the compression zone of concrete is outside the hollow section; therefore, it does not affect the moment capacity. The moment capacity slightly decreases when the *d/D* ratio is 0.55. Further increasing the *d/D* ratio, there is a clear decreasing trend in moment capacity. When there is no infill concrete, the moment capacity is 1064.5 kNm. This characteristic is also found for CFST sections with *D/t* of 53.5 and 78.2, as presented in Figure 6b and c. However, the ratio of *d/D* at the starting reduction in the ultimate moment is slightly increased to 0.55 and 0.6 for CFST sections with *D/t* of 53.5 and 78.2, respectively.
Figure 7a shows the reduction percentages of moment capacities compared with the solid CFST sections with a *D/t* of 40.64. There is no reduction when the *d/D* ratio is up to 0.50, while the reduction of the ultimate moment starts at 0.55, which corresponds to the percentage of hollow area to the whole area of 30.25%. When further increasing the *d/D* ratio to 0.95, the reduction percentage increases significantly to 15.4%. This reduction percentage also indicates the limited contribution of the infill concrete to the moment capacity of CFST beam sections.
Figure 7b and c indicate a similar characteristic for CFST sections with *D/t* of 53.5 and 78.2; however, the ratio *d/D* of the starting reduction of the ultimate moment is slightly increased to 0.60 and 0.65, respectively. Therefore, when *D/t* increased from 40.64 to 53.5 and 78.2, the threshold values of *d/D* increased from 0.50 to 0.60 and 0.65, respectively. These results indicate the more important role of concrete in CFST sections with a higher *D/t* ratio. Figure 7 also reveals that the contribution of the concrete infill to the moment capacity was 15.4% to 19.8% for CFST sections, with *D/t* varying from 40.64 to 78.2, respectively.

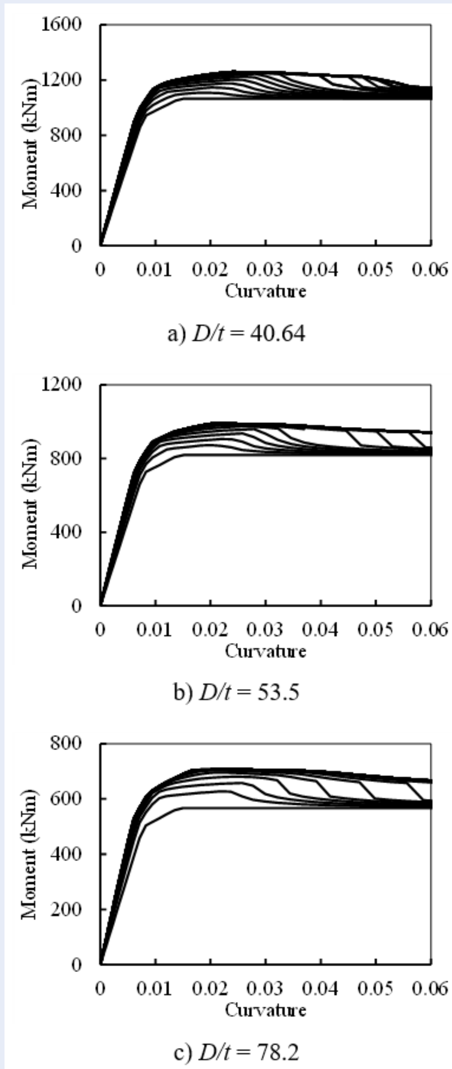

Figure 5: Moment-curvature curves of CFST sections with different hollow sections.

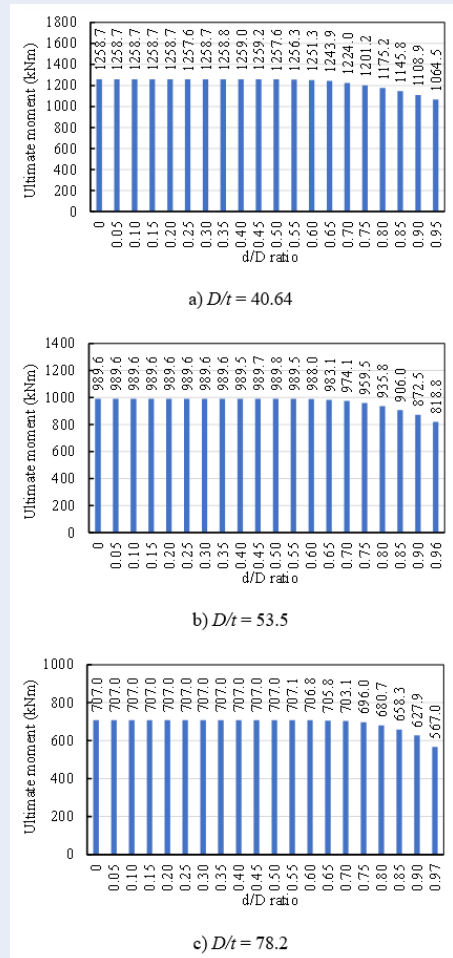

Figure 6: Variation in ultimate moment with respect to *d/D* for CFST sections

CONCLUSIONS

In this study, 60 fiber-sectional analyses of CFST sections with *D/t* of 40.64, 53.5, and 78.2 were performed. The effect of hollow concrete sections was analysed and led to the following conclusions. The moment–curvature curves are moderately affected by the hollow concrete sections. The moment curvature curves were almost unchanged when the ratio of *d/D* was up to 0.55, at which the hollow area was approximately 30% of the total sectional area of CFST. Moment capacity of CFST sections decreases when further increases the *d/D* ratio beyond 0.55. When *d/D* ratio is close to its maximum value (ST beams), the decreasing percentage of moment curvature was 15.4%–19.8%. Based on the obtained results, the hollow sections were recommended to be limited at 0.55, which corresponds to approximately 30% of the cross-sectional area of CFST sections. It is worth noting that these conclusions are applied for sections under pure bending. Further experimental and finite element studies should be carried out for CFST sections with hollow sections under combinations of bending moment and axial loading. Additionally, local buckling of steel tubes in such analyses should be further investigated.

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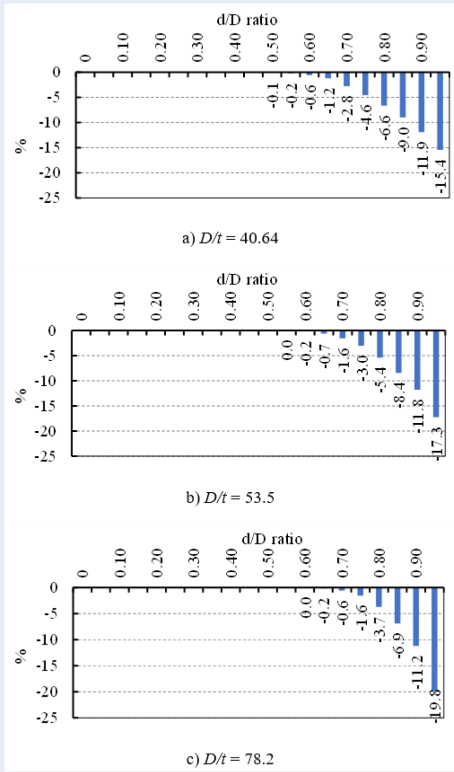

Figure 7: Reduction percentage of moment capacity of CFST sections with respect to *d/D*.

CONFLICT OF INTEREST

No conflict of interest.

AUTHOR CONTRIBUTION

Khanh Ba Le: Conceptualization, Methodology, Analyses, Check the paper; Vui Van Cao: Modelling, Write the draft of the paper.

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Ảnh hưởng của tiết diện bê tông rỗng đến khả năng chịu mô men uốn thuần túy của dầm ống thép nhồi bê tông tròn

Lê Bá Khánh[1,2], Cao Văn Vui[1,2,*]

TÓM TẮT

So với bê tông cốt thép, ống thép nhồi bê tông (CFST) có một số ưu điểm do sự tương tác cùng có lợi giữa ống thép và bê tông. Một số lượng lớn các nghiên cứu về cột CFST đã được thực hiện; trong khi đó, các nghiên cứu về dầm CFST dường như rất ít được nghiên cứu. Vì vậy, nghiên cứu dầm CFST cần được khuyến khích để xây dựng kết cấu khung dầm–cột CFST. Khi dầm CFST chịu mô men uốn, các mặt cắt của nó được chia thành vùng nén và vùng kéo. Diện tích bê tông gần trục trung hòa có thể tham gia một cách hạn chế vào khả năng chịu uốn của tiết diện CFST; do đó, nó có thể được làm rỗng để giảm trọng lượng bản thân và chi phí. Vì vậy, bài báo này nghiên cứu ảnh hưởng của tiết diện bê tông rỗng đến khả năng chịu mô men của dầm CFST. Mặt cắt dầm CFST được chọn và mô hình thớ của nó đã được xây dựng và kiểm chứng. Sau đó, tổng cộng 60 mặt cắt có ba tỷ lệ đường kính trên độ dày (*D/t*) là 40,64, 53,5 và 78,2 đã được phân tích và so sánh. Ảnh hưởng của các tiết diện bê tông rỗng đã được phân tích và đưa ra các kết luận. Kết quả chỉ ra rằng các đường cong quan hệ giữa mô men uốn và góc xoay bị ảnh hưởng vừa phải bởi các mặt cắt bê tông rỗng. Kết quả cũng cho thấy diện tích bê tông có thể được làm rỗng lên tới 30,25% tổng diện tích mặt cắt CFST. Diện tích rỗng có thể tăng lên tới 42,25% khi tỷ lệ *D/t* tăng lên. Kết quả cũng chỉ ra rằng phần bê tông nhồi đóng góp 15,4%–19,8% vào khả năng chịu mô men của tiết diện CFST. Sự đóng góp của bê tông nhồi đối với khả năng chịu mô men của tiết diện CFST tăng nhẹ khi tỷ lệ *D/t* tăng. Những kết quả này có thể là thông tin hữu ích cho các kỹ sư kết cấu khi thiết kế dầm CFST tròn có tiết diện bê tông rỗng.

Từ khoá: Khả năng chịu mô men, Ống thép nhồi bê tông (CFST), Dầm, Mặt cắt rỗng, Uốn

[1] *Khoa Kỹ Thuật Xây Dựng, Trường Đại học Bách Khoa Tp. Hồ Chí Minh, 268 Lý Thường Kiệt, Phường 14, Quận 10, TP. Hồ Chí Minh*

[2] *Đại học Quốc Gia Tp. Hồ Chí Minh, Phường Linh Trung, TP. Thủ Đức, TP. Hồ Chí Minh*

Liên hệ

Cao Văn Vui, Khoa Kỹ Thuật Xây Dựng, Trường Đại học Bách Khoa Tp. Hồ Chí Minh, 268 Lý Thường Kiệt, Phường 14, Quận 10, TP. Hồ Chí Minh

Đại học Quốc Gia Tp. Hồ Chí Minh, Phường Linh Trung, TP. Thủ Đức, TP. Hồ Chí Minh

Email: cvvui@hcmut.edu.vn

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