**UNIVERSITI PUTRA MALAYSIA**

# *STRUCTURAL BEHAVIOR AND ENVIRONMENTAL IMPACT OF PRECAST ULTRA-HIGH PERFORMANCE DUCTILE CONCRETE CANTILEVER RETAINING WALLS*

**BEHZAD NEMATOLLAHI**

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By

**BEHZAD NEMATOLLAHI**



**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science**

**May 2012**

Dedicated to the author's beloved Father and Mother

Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Master of Science

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**Chairman: Raizal Saifulnaz Muhammad Rashid, PhD**

**Faculty: Engineering**

One of the main breakthroughs in concrete technology in the 20th century was the development of the steel fiber reinforced ultra high performance concrete (SFR-UHPC), also known as steel fiber reinforced reactive powder concrete (SFR-RPC) and more commonly known as ultra high performance 'ductile' concrete (UHPdC) with compressive strength over 150 MPa and flexural strength over 30 MPa and remarkable improvement in durability compared to conventional concrete. Recently, due to the improved society awareness regarding the destructive effects of global warming, there is strong concern to minimize the environmental impacts (e.g. $CO_2$ emission, embodied energy (EE)) of our structural designs. One of the solutions to achieve this goal is using the UHPdC technology which can offers considerable advantages through the efficient use of material and optimization of the structural design.

Based on the revolutionary properties of UHPdC, it can offer remarkable benefits when it is utilized, as a new generation of sustainable construction material, in the fabrication of precast members for civil engineering, structural and architectural applications such as precast reinforced concrete (RC) cantilever retaining walls. On the basis of the available literature on UHPdC, no study has been carried out on the structural behavior and environmental impacts of precast UHPdC cantilever retaining walls. Further, to date there are no specific design codes/standards for analysis, design, and construction of the UHPdC structures. Therefore, this study attempted to fill this gap by evaluating the structural behavior and environmental impacts of the precast UHPdC cantilever retaining walls compared against the conventional precast RC cantilever retaining walls as benchmark of this study.

In this regard, at first the geotechnical analysis of the precast UHPdC wall was carried out in accordance with Eurocode 7 (EC7): Geotechnical design- Part 1: General rules (2004) requirements. Subsequently, it was structurally designed based on the first principles (equilibrium equations) in conjunction with the Japanese Society of Civil Engineers' Recommendations for Design and Construction of Ultra High Strength Fiber Reinforced Concrete Structures (Draft) (JSCE No.9, 2006). Afterwards, the reliability of the precast UHPdC wall was ascertained through the experimental tests with full-scale wall specimens. Four UHPdC wall specimens with the dimensions of 2.5 m in height, 2 m in length, and 2 m in width were casted. The area of the steel bars ($A_s$) used in the wall stem and the volumetric ratio of the steel fibers ($\rho_s$) used in the UHPdC composite were the test parameters. The mechanical properties of the cubes and prisms (including the cube compressive strength, flexural toughness and first cracking strength) casted from the same UHPdC composite for the wall specimens were also measured. Three wall specimens (denoted as Wall1, Wall3 and Wall4) were casted with 1.5% of steel fibers by volume of UHPdC and the test parameter was the $A_s$ used in the stem which were 628 $mm^2$ (2T20) in Wall1, 982 $mm^2$ (2T25) in Wall3, and 1608 $mm^2$ (2T32) in Wall4. Whilst, the other wall specimen (denoted as Wall2) was casted with 1.0% of steel fibers by volume of UHPdC. The $A_s$ used in the stem of Wall2 was exactly equal to that of Wall3 (i.e. 2T25) to evaluate the effect of the $\rho_s$ in the UHPdC composite on the structural behavior of the wall specimen. The RC cantilever retaining wall with the dimensions of 2.5 m in height, 1 m in length, and 2.35 m in width was also analyzed with exactly the same loading, soil and ground water table conditions based on the EC7 requirements and structurally designed in accordance based on Eurocode 2 (EC2): Design of concrete structures- Part 1-1: General rules and rules for buildings (2004) to be used as the benchmark. Lastly, the environmental impact calculation (EIC) of the UHPdC wall was compared to the RC wall to prove that the UHPdC wall is a green structural member supporting the concept of sustainable development.

According to the results of the experimental tests on the UHPdC wall specimens, all the specimens exhibited displacement hardening behavior after occurrence of the first crack due to inclusion of very high strength micro steel fibers bridging the cracks and limiting the crack propagation. Based on the results of Wall1, Wall3 and Wall4, the increase in the $A_s$ in the wall stem led to the noticeable increase in the failure load of the specimens. Based on the results of Wall2 and Wall3, the increase in the $\rho_s$ in the UHPdC composite of the wall led to the relative increase in the wall toughness causing a relative increase in the failure load of the specimen. In all of the wall specimens, the ratio of the experimental failure load to the expected failure load was on average equal to 0.66. This is due to the occurrence of the bond failure between 4T16 rebars on top of the wall heel and the UHPdC composite, resulted in the wall base failure prior to reaching the ultimate moment capacity of the wall stem (i.e. the wall stem failure). Hence it can be concluded that although based on the structural design, the area of 4T16 rebars were adequate (i.e. $M_{Ed} < M_{Rd}$); however, based on the experimental tests, they were not sufficient and should be increased to 4T20 or 4T25 in future wall design. Based on the EIC results with using the UHPdC wall, 86% saving in terms of material consumption, 57% saving in terms of EE, 60% saving in terms of $CO_2$ emission, and 61% saving in terms of 100 year global warming potential (100 yr-GWP) can be achieved. Comparisons between the UHPdC wall and the conventional RC wall as the benchmark and the results of the EIC of both walls proved that the UHPdC wall is an alternative sustainable solution and a green structural member supporting the concept of sustainable development which has superior properties in all aspects compared to the conventional RC wall.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

**PERLAKUAN STRUKTUR DAN IMPAK ALAM SEKITAR TEMBOK PENAHAN JULUR KONKRIT PRATUANG MULUR BERPRESTASI ULTRA-TINGGI**

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Salah satu penemuan utama dalam teknologi konkrit dalam abad ke-20 adalah pembangunan gentian keluli bertetulang konkrit prestasi ultra tinggi (SFR-UHPC), juga dikenali sebagai konkrit serbuk reaktif (RPC) dan lebih dikenali sebagai konkrit mulur berprestasi ultra tinggi (UHPdC) dengan kekuatan mampatan lebih daripada 150 MPa dan kekuatan lenturan lebih daripada 30 MPa dan perbaikan yang luar biasa dalam ketahanan berbanding konkrit biasa. Baru-baru ini, disebabkan kesedaran masyarakat yang lebih baik mengenai kesan kemusnahan pemanasan global, terdapat kebimbangan yang kuat untuk meminimumkan impak alam sekitar (seperti $CO_2$ pelepasan, tenaga yang terkandung) rekabentuk struktur kita. Salah satu penyelesaian bagi mencapai sasaran ini adalah dengan mengunakan teknologi UHPdC yang boleh menawarkan kelebihan melalui penggunaan bahan yang effisen dan rebebentuk struktur yang optimum.

Berdasarkan sifat-sifat revolusi UHPdC, ia boleh menawarkan faedah yang luar biasa apabila ia digunakan, sebagai generasi baru bahan binaan yang mampan, dalam pengeluaran elemen pratuang bagi kejuruteraan awam, aplikasi struktur dan seni bina seperti tembok penahan julur pratuang konvensional konkrit bertetulang (RC). Berdasarkan literatur yang ada berkaitan UHPdC, tiada kajian dijalankan ke atas konkrit bertetulang tembok penahan julur pratuang UHPdC yang konvensional. Lebih-lebih lagi, sehingga kini tiada garis panduan reka bentuk / standard untuk analisis, reka bentuk dan pembinaan struktur UHPdC. Oleh itu, penyelidikan bagi memahami kelakuan struktur tembok penahan julur pratuang UHPdC berbanding tembok penahan konkrit bertetulang julur pratuang konvensional ditetapkan sebagai halatuju kajian ini.

Dalam hal ini, untuk kali pertama dinding pratuang UHPdC julur dianalisis mengikut Eurocode 7 (EC7): Rekabentuk Geoteknik Bahagian 1: Menggunakan kaedah (EN 1997-1:2004) dan kemudian struktur direka berdasarkan prinsip yang pertama menggunakan kaedah yang disyorkan oleh Kumpulan Jurutera Awam Jepun 'bagi reka bentuk dan pembinaan struktur UHPdC (Draft) (JSCE No.9, 2006). Kebolehpercayaan dinding pratuang UHPdC diuji melalui ujian perintis dengan spesimen dinding berskala penuh. Dalam ujian perintis, empat skala penuh UHPdC dinding spesimen dengan dimensi 2.5 m tinggi, 2 m panjang dan 2 m lebar dibina. Keluasan bar keluli yang digunakan dalam penupang dinding spesimen, dan nisbah isipadu gentian keluli yang digunakan dalam reka bentuk campuran UHPdC adalah pemboleh ubah ujikaji. Sifat-sifat mekanik yang dilihat penting dalam ujikaji ini adalah kekuatan kiub mampatan, keliatan lenturan dan retak pertama kekuatan kiub dan prisma yang diambil daripada campuran yang sama UHPdC digunakan untuk menetukan setiap spesimen dinding diukur mengikut piawaian yang ditetapkan. Tiga spesimen dinding berskala penuh (ditandakan sebagai Wall1, Wall3 dan Wall4) dibina dengan jumlah sebanyak 1.5% mengikut isipadu gentian keluli UHPdC dan parameter ujikaji adalah keluasan tetulang besi yang digunakan dalam tiang dinding spesimen dimana 628 mm2 (iaitu 2T20) dalam Wall1, 982 mm2 (iaitu 2T25) dalam Wall3, dan 1608 mm2 (iaitu 2T32) dalam Wall4. Sementara itu, skala penuh dinding spesimen yang lain (ditandakan sebagai Wall2) adalah dibina dengan jumlah sebanyak 1.0% isipadu gentian keluli UHPdC. Keluasan bar keluli yang digunakan di dalam tiang Wall2 adalah betul-betul sama dengan Wall3 (i.e. 2T25) bagi mengkaji kesan $\rho_s$ dalam campuran UHPdC yang digunakan bagi kelakuan struktur tiang dinding spesimen. Tembok penahan julur konkrit bertetulang berketinggian 2.5m, 1m panjang dan 2.35 lebar telah juga dianalisis dan direka bentuk dengan beban, tanah dan keadaan air bawah tanah berdasarkan keperluan yang diberikan dalam EC7 dan direkabentuk struktur berdasarkan Eurocode 2 (EC2): Rekabentuk struktur konkrit Bahagian 1-1 : Peraturan umum dan peraturan bangunan (2004) untuk digunakan sebagai rujukan kajian ini. Akhir sekali, enviromental impact calculation (EIC) UHPdC telah dibandingkan dengan dinding konkrit bertetulang RC bagi membuktikan bahawa dinding tersebut adalah struktur hijau bagi menyokong konsep pembangunan mampan.

Menurut keputusan ujikaji keatas spesimen dinding UHPdC, semua spesimen mempamerkan perlakuan anjakan pengerasan selepas keretakan pertama berlaku pada disebabkan oleh gentian keluli merapatkan mikro-retak dan menghadkan pergerakkan retak. Keputusan ujian perintis Wall1, Wall3, dan Wall4 menunjukkan bahawa peningkatan $A_s$ yang digunakan dalam tiang dinding yang membawa kepada peningkatan yang agak tinggi bagi beban kegagalan spesimen dinding. Keputusan uji kaji Wall2, dan Wall3 menunjukkan bahawa peningkatan $\rho_s$ dalam campuran UHPdC spesimen dinding menyebabkan peningkatan dalam keliatan dinding; dengan itu, beban kegagalan percubaan dinding telah meningkat secara relatifnya.

Dalam semua spesimen dinding, nisbah beban kegagalan ujikaji berbanding beban kegagalan ujikaji yang dijangka adalah secara purata kepada 0.66. Ini adalah kerana berlakunya kegagalan lekatan antara tetulang 4T16 pada bahagian atas tumit dinding penahan dan komposit UHPdC yang menyebabkan kegagalan asas dinding penahan sebelum ia mencapai kapasiti momen muktamad dinding penahan (i.e kegagalan dinding penahan). Oleh itu, bolehlah dibuat kesimpulan bahawa walaupun berdasarkan reka bentuk struktur, kawasan tetulang 4T16 adalah mencukupi (i.e. $M_{Ed} < M_{Rd}$), walaubagaimanapun, berdasarkan ujikaji ekperimen, ia adalah tidak mencukupi dan perlu ditambah kepada 4T20 atau 4T25 pada rekabentuk bagi ujikaji akan datang. Berdasarkan keputusan EIC dengan menggunakan dinding UHPdC, penjimatan sebanyak 86% dari segi penggunaan bahan, 57% penjimatan dari segi EE, 60% penjimatan dari segi pelepasan CO2, dan 61% penjimatan dari segi potensi pemanasan global 100 tahun (100 tahun-GWP) boleh dicapai. Perbandingan antara dinding UHPdC dan dinding konvensional RC sebagai penanda aras dan keputusan EIC kedua-dua dinding membuktikan bahawa dinding UHPdC adalah penyelesaian alternatif yang mapan dan struktur hijau yang menyokong konsep pembangunan mampan yang mempunyai ciri-ciri unggul dalam semua aspek berbanding dinding RC konvensional.

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I certify that a Thesis Examination Committee has met on **22 May 2012** to conduct the final examination of **BEHZAD NEMATOLLAHI** on his thesis entitled **"STRUCTURAL BEHAVIOR AND ENVIRONMENTAL IMPACT OF PRECAST ULTRA-HIGH PERFORMANCE DUCTILE CONCRETE CANTILEVER RETAINING WALLS"** in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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**DECLARATION**

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institutions.

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**BEHZAD NEMATOLLAHI**

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