UK-CHINA SCIENCE BRIDGE - SUSTAINABLE SOLUTIONS FOR THE BUILT ENVIRONMENT

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ABSTRACT
The remit of the UK-China Science Bridge focussing on sustainable energy and built environment is to accelerate the deployment of research knowledge from Queen’s University Belfast to leading Chinese universities and research institutions who are partners of the bridge. As the emphasis of this Science Bridge is sustainable energy and built environment, the aim is to undertake proof of concept studies on Queen’s University-developed technologies in this field at leading Chinese universities and research centres. Particular attention is given to non-destructive testing and sensors for monitoring the durability of structures as well as a novel form of construction called ‘flexible arch’. The Chinese counterparts aim to set up monitoring systems in concrete bridges where the sensor systems from Queen’s will be employed. Data from these monitoring stations will be used to predict the service life and the structural health performance of concrete bridges in marine environments. The aim of this paper is to introduce this international collaborative programme and describe the research undertaken so that other organisations can benefit from the outcomes.

BACKGROUND
In 2006, the UK Government introduced financial support for UK institutions with existing research links to world-class universities and high-tech businesses in selective partnering countries. The required remit of funded collaborations, or science bridges, is to accelerate the deployment of research knowledge, deepen and strengthen current research links, undertake proof-of-concept studies, enable the acquisition of new skills, and encourage wealth creation by improving the transfer of research and expertise from the research base to businesses and other users.

With an initial focus on partnerships between the UK and US, the most recent round of science bridge awards extended to include the emerging super-economies of China and India. In 2008, three awards each were funded with the US and India and four with China. With 42 applications, compared to 26 and 20 for the US and India respectively, competition for UK-China science bridge awards was intense. Selected in collaboration with the Chinese Ministry of Science and Technology, the four winning UK-China bridges received funding totalling £4.412 million over three years from the Research Councils UK.

Led by research teams from the Schools of Electronics, Electrical Engineering and Computer Science (EEECS) and Planning, Architecture and Civil Engineering (SPACE), a team from Queen’s University Belfast successfully secured one of the four UK-China Science Bridge awards. Table 1 gives details of project partners in the Queen’s University’s UK-China Science Bridge project. With a dual focus of developing innovative and sustainable solutions relating to energy production and the built environment, this is the sole Science Bridge project, from all 10 awarded between China, India and the US, with a construction focus. The remit of this paper is to provide an overview of the built environment-related element of Queen's University's UK-China Science Bridge project.

Table 1. Project Partners for Queen's University's UK-China Science Bridge Project

UK	CHINA
Academic	
• Queen's University Belfast - School of Planning, Architecture and Civil Engineering - School of Electronics, Electrical Engineering and Computer Science	• Chongqing University • Hunan University • Shanghai Jiao Tong University • Shanghai University • Southeast University • Tsinghua University • Zhejiang University
Research Institutions	
	• Central Research Institute of Building & Construction • Research Institute of Highways, Ministry of Transport • Chinese Academy of Sciences Institute of Electrical Engineering
Industrial	
• Amphora Non-Destructive Testing Ltd. • Macrete Ltd • SUPERGEN Partners	• China State Construction Engineering Corporation • China State Railway Construction Group • Shanghai Bao Steel Group Corporation Ltd. • Shanghai Electric Group Corporation Ltd.

NEED FOR A BUILT ENVIRONMENT-RELATED SCIENCE BRIDGE

Chinese construction industry

With one of the fastest growth rates in the world, the outlook for the $5 trillion construction industry in China is strong. A rapidly expanding domestic economy, continuing efforts to upgrade physical infrastructure, sustained strength in foreign investment funding, healthy demand for Chinese manufactured goods, ongoing urbanisation and further population and household growth are all responsible for the spends in the construction market [Freedonia Group, 2008]. Infrastructure is predicted to be the fastest growing sector up to and beyond 2012, with growth fuelled by government initiatives to expand and upgrade the country's physical infrastructure; in particular its highways, railways and subway systems. Utilities construction will also predominate, as the government continues to increase the country's power generation capacity and improve electricity transmission networks, as well as expand and improve municipal water supply coverage and natural gas distribution.

Sustainable development

The combination of rapid economic growth, high rates of urbanisation and energy demand poses significant challenges for China in terms of sustainable development. China is currently the largest producer and consumer of steel, cement, and coal, and owing to its heavy reliance on the latter, is the second largest producer of greenhouse gases after the USA. Recent statistics show that China overtook the USA in CO_2 emissions in 2007, with a figure of 1.802 billion ton of CO_2 in total, which is an increase of 105% from 1996 [Malhotra, 2010]. Encouragingly, however, not only is sustainable development official government policy in China, but it is also being implemented in some regions at a pace that far outstrips anything seen in Europe. Driven, in part, by China's goal of achieving a 'green' Olympics in 2008, the Chinese government has strengthened environmental legislation and reported planned investments of around $12 billion in the period 1998 to 2007 [Diesendorf, 2003]. According to Malhotra, [2010], China tops in investment on green energy technologies. Indeed, the Chinese 11th Five-Year Plan considers innovation and sustainability in the built environment to be crucial for achieving universal sustainable development. The plan clearly identifies the need to change the mode of economic growth, make resource conservation a basic national policy, build a resource-efficient and environmentally friendly society, promote economic development in harmony with population, resources and the environment, and achieve sustainable development [Yan, 2006].

Role of the built environment

The volume of concrete currently being placed in China exceeds that at any other time in human history; 700 million tons of cement were manufactured and consumed in China in 2002, representing about half of global output. However, partly due to a focus on high-speed construction, premature deterioration of reinforced concrete structures in China is commonplace, as evidenced by extensive damage caused in recent earthquakes. A specific example reported in the literature includes the section of freeway concrete pavement between Shenzhen and Shantou in south China, which experienced considerable levels of cracking and deterioration after only 6-12 months [Qin, 2004]. With the built environment representing approximately 50% of China's national wealth, these durability issues have serious economic consequences and, perhaps not surprisingly, the direct link between durability of concrete structures and sustainable development is reported in the literature [Qin, 2004].

SCOPE OF WORK

The primary aim of the UK-China Science bridge project is to enable China to address its infrastructure-related issues in a sustainable manner, without hindering economic progress. Concurrently, the UK should benefit from an enhanced uptake of its technology, knowledge and expertise through enhanced business opportunities and strengthened collaboration with key Chinese institutions and companies. Against this background, the scope of the project can be broken down into five principal activities as highlighted in Figure 1 and discussed below.

Activity 1: Proof-of-concept testing

Due to the documented premature durability problems of concrete structures in China, a demand exists for simple, reliable *in situ* tests to assess and improve quality control. This fact has also been corroborated by the findings of previous UK-China collaborations. For this purpose, Activity 1 will assess the appropriateness of three instruments developed at QUB – namely the Autoclam [Basheer *et al*., 1994], Permit [Nanukuttan *et al*., 2006] and Limpet [Long, 1983] tests. Co-funded by Chinese agencies and undertaken as sub-contracts to Queen's University's Science Bridge project, proof-of-concept tests will be carried out in China by Tsinghua University, Zhejiang Universities and the Central Research Institute of Building and Construction (CRIBC). The intention of this work will be to assess the reliability and repeatability of the test methods; develop relationships between on site tests and existing laboratory-based tests covered by Chinese Standards; and to prepare documentation to support the acceptance and standardisation of these test methods in China. This China-based work will be supported by research at Queen's University to enable wider application to specialised areas, such as the assessment surface treatments and high performance materials.

Activity 2: Technology transfer activities

The goal of this work is to promote uptake of UK-developed test methods and technologies through the delivery of demonstration projects in China. In addition to demonstrating the Autoclam, Permit and Limpet tests, novel sensor systems for monitoring reinforced concrete structures and a flexible arch system developed by Queen's University, will be included in this work. Working in collaboration with Chinese partners, including the CRIBC, China State Railway Construction Group Corporation Ltd, China State Construction Engineering Corporation and Zhejiang University, the test methods for assessing in situ quality of concrete will be demonstrated on the 'Beijing to Shanghai high speed railway' and selected sea bridge' projects. The 'flexible arch' demonstration project will also be undertaken in collaboration with Zhejiang University, Chongqing University and relevant industrial partners. The ultimate aim of this work is to encourage the uptake of these instruments and technology by the Chinese construction industry.

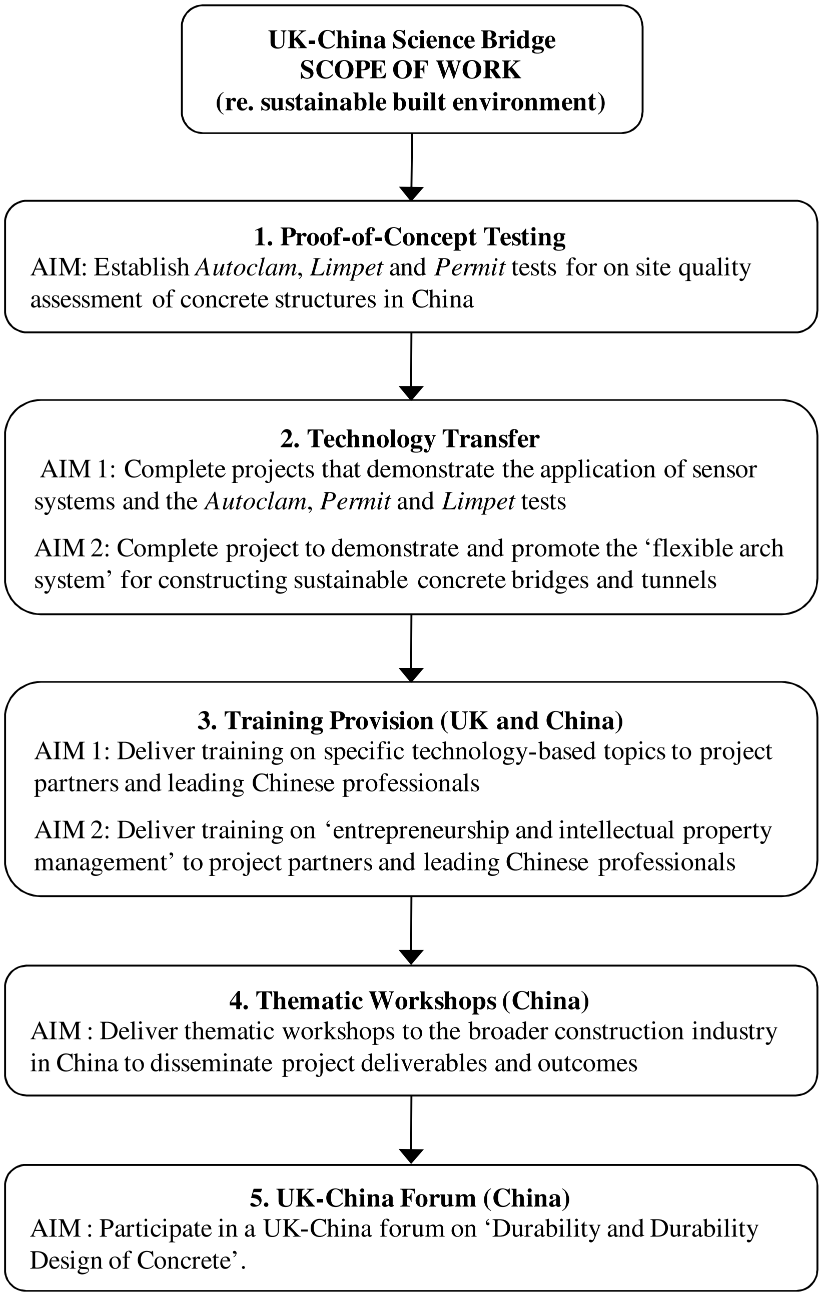


Figure 1. Overview of UK-China Science Bridge project

Activity 3: Training programmes

As successful technology transfer requires industry to accept new concepts and technology and for individuals to equip themselves with relevant skills, Activity 3 will involve training packages aimed at leading Chinese professionals. Initially delivered in the UK with a primary focus on the Queen's University-developed technology, this activity will expand to encompass events in China and the development of on-going training programmes aimed at professionals in both the UK and China.

In addition to concrete-specific topics, the training delivered as part of Activity 3 will additionally cover the topic of ‘entrepreneurship and intellectual property management’. With a long-standing tradition of providing excellent training in his field to their students and with high success rates in terms of spin-out companies and national business plan competitions, Queen’s University is well placed to deliver this package of training. Technology transfer internships will be additionally be offered to Chinese partners to undergo training at Queen’s University on this topic.

Activity 4: Thematic workshops

In addition to delivering training to leading professionals and project partners, the scope of Activity 4 will be broadened to disseminate project outcomes to the wider construction industry and public to ensure complete and successful technology transfer. Thematic workshops entitled Durability of concrete structures – mechanisms of deterioration, measures to extend service life and investigation techniques and sustainable and low carbon systems for novel arch construction will be held in collaboration with the CRIBC, assisted by Tsinghua University, and Chongqing and Zhejiang Universities respectively.

Activity 5: UK-China forum

To enable continuation of the required breadth and depth of the UK-China collaboration and associated knowledge transfer activities, an international forum entitled ‘Durable Built Environment’ will be delivered along with Chinese partners. This forum will also allow policy makers to be informed of continued developments in the field of sustainable solutions in the built environment.

TECHNOLOGIES OFFERED

As illustrated in Figure 2, various environmental agents (such as carbon dioxide, chlorides, sulphates, water and oxygen) and their interactions with cement hydrates in concrete are the primary reasons for deterioration of concrete. The phase prior to the onset of deterioration is normally referred to as the ‘initiation phase’ (Figure 3). All deterioration mechanisms initially cause microcracking of concrete, which becomes severe as the action continues (‘propagation phase’ in Figure 3). In some cases widespread cracking of concrete is the final outcome, while in other cases, such as the corrosion of reinforcement in concrete, delamination and spalling of concrete may also occur. The extent of microcracking, cracking and spalling depends on the fracture strength of concrete, which is also dependent on the microstructure of concrete. In all cases, deterioration of concrete leads to further increase in the transport, as illustrated in Figure 2, which in turn, increases the rate of deterioration or initiates some other form of deterioration.

Figures 2 and 3 suggest that most structures are likely to encounter one or more forms of deterioration, unless preventive maintenance is carried out on an ongoing basis to increase the time before initiation of deterioration. As illustrated in Figure 2, permeation properties (such as sorptivity, permeability and diffusivity) and fracture strength of concrete are two important characteristics that decide the time before the initiation of deterioration (part of service life designated by t_0 in Figure 3). During this phase, information on the ingress of deleterious substances into the structure and/or their effects on the microstructure of concrete can also be used to determine t_0. The data thus obtained are invaluable for scheduling when to carry out cost-effective repair and rehabilitation works. *In situ* non-destructive tests for fracture strength and permeation properties (viz. sorptivity, permeability and diffusivity) and sensors which can be either embedded in new, or retrofitted in existing, structures can provide valuable data from a structure on a continuous basis. Therefore, three different non-destructive tests and various sensor systems specifically developed for these purposes have been considered for technology transfer activities. Complimentary investigation will be carried out by the project partners to use field data from NDTs and sensors in service life prediction models. Some of these test techniques and sensors can also be used to quantify the rate of deterioration during the active phase (see Figure 3), thus contributing to the estimation of time before end of service life has reached (t_f in Figure 3).

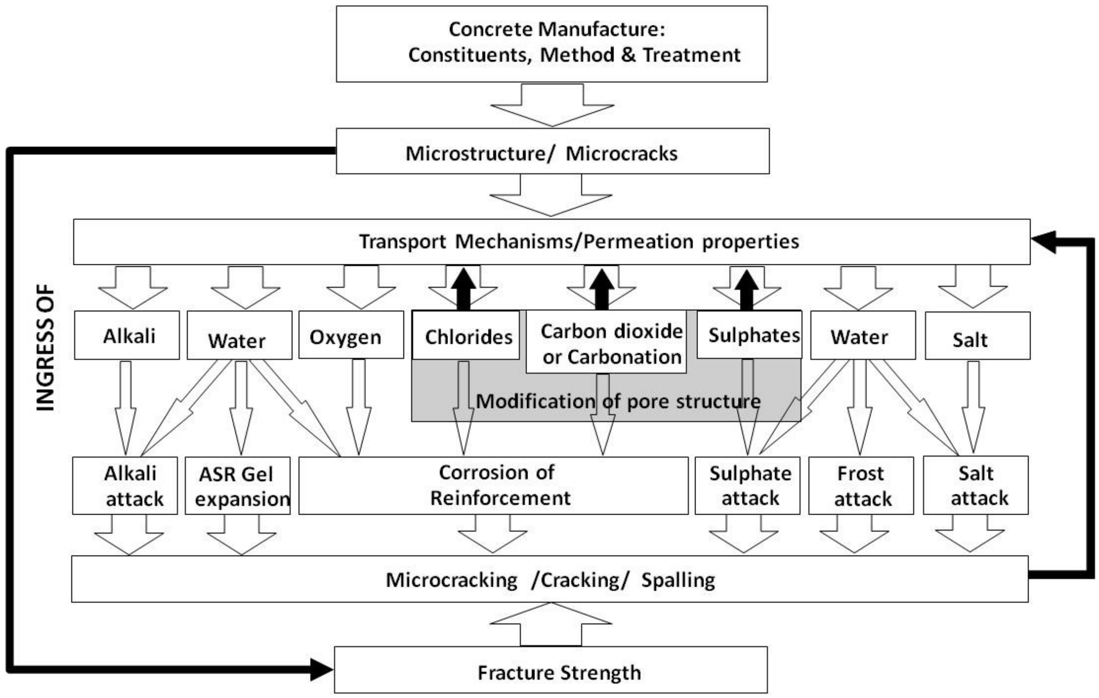


Figure 2. Interdependence of microstructure, permeability, fracture strength and deterioration of concrete (Basheer *et al.*, 2005)

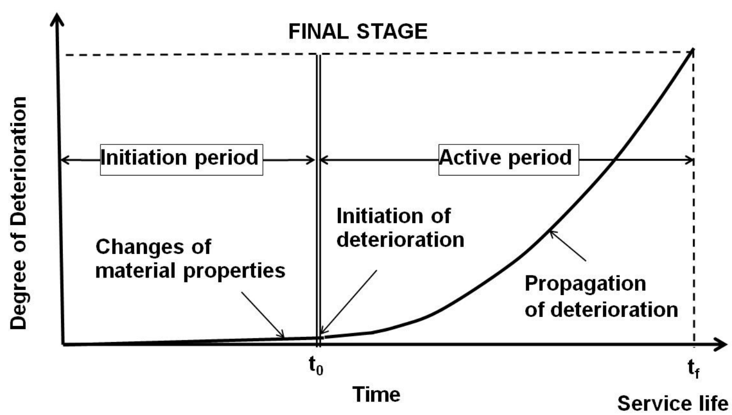
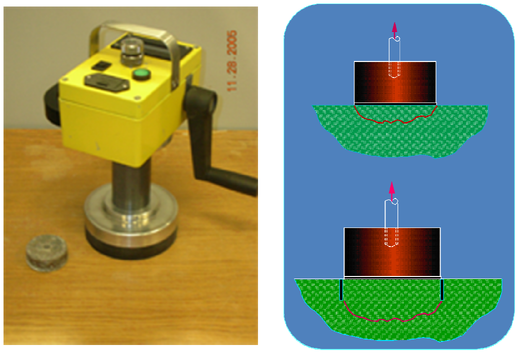


Figure 3. Components of service life of a concrete structure

<u>Limpet Pull-Off test</u>

The Limpet Pull-off Test (Figure 4) measures the *in situ* tensile strength of cover concrete by applying a direct tensile load via a disc bonded on the surface. Through empirical correlations the compressive strength can be predicted from the pull-off strength. However, this test is commonly used nowadays to determine the bond strength of concrete patch repairs, assess the effects of curing and carbonation of concrete and to determine the effect of microcracking. The pull-off test is carried out using two approaches (Figure 4). Firstly, where a metal disc is directly attached to a concrete surface allowing strength measurements and, secondly, where concrete is cored to a depth to eliminate the influence of carbonated layers and to allow strength measurement at a given depth. The approach of partial coring is used quite extensively for testing the bond strength of concrete patch repairs (BS EN 1542; ASTM C1583). The main advantage of the pull-off test is that it is simple and quick to perform and no pre-planning is required to avoid reinforcement.



Bonding type

Bolt on type

Figure 4. Limpet Pull-off Tester

Figure 5. Autoclam permeability system

<u>Autoclam Permeability System</u>

The Autoclam Permeability system (Figure 5) was developed to measure the sorptivity, air permeability and water permeability of concrete cover on site (Basheer *et al.*, 1994). Normally these tests are performed by isolating a test area of 50mm diameter using either a bonding type ring or a bolt-on type ring (Figure 5). Less permeable surfaces are tested with a larger contact area and normalising the data thus obtained to the standard 50 mm diameter. Although moisture influences the test results, Basheer and Nolan (2001) have shown that the quality of concrete can be classified using the Autoclam permeability indices if tests are carried out when the internal relative humidity of concrete in the cover zone, up to a depth of 10 mm, is less than 80%. Table 2 reports a tentative classification of concrete quality based on the Autoclam permeation indices. The test was used to assess the quality of concrete in notable structures, such as Bird Nest National Stadium in Beijing (Figure 6).

Table 2. Classification of concrete based on Autoclam permeation indices (Basheer, 1993)

Permeation Property	Protective quality			
	Very Good	Good	Poor	Very Poor
Autoclam Sorptivity Index ($m^3 \times 10^{-7}/\sqrt{min}$)	≤1.30	>1.30≤2.60	>2.60≤3.40	>3.40
Autoclam Water Perm. Index ($m^3 \times 10^{-7}/\sqrt{min}$)	≤3.70	>3.70≤9.40	>9.40≤13.8	>13.80
Autoclam Air Perm. Index (ln(pressure)/min)	≤0.10	>0.10≤0.50	>0.50≤0.90	>0.90

Figure 6. Autoclam used to test concrete in Bird Nest National Stadium, Beijing, China

Permit ion migration test

Developed on the principle of ionic migration, the Permit ion migration test (Figure 7) enables *in situ* determination of the resistance of concrete cover to chloride transport. Through extensive laboratory research, the test provides a coefficient of ionic transport in m^2/s (Basheer *et al.*, 2005; Nanukuttan *et al*, 2006). It has also been established that Permit ion migration test results correlate well with conventional laboratory-based steady state diffusion and migration coefficients. The main advantage of this test is that it provides a migration coefficient without having to remove cores from a structure. Figure 8 shows the Permit being used to assess the effectiveness of different methods of improving the chloride ion penetration resistance of the Qingdao Bay Bridge in China.

Figure 7. Permit Ion Migration Test

Figure 8. Permit being used in Qingdao Bay Bridge in China

Covercrete Electrode Array Sensor

The primary function of the Covercrete Electrode Array developed by McCarter *et al.* at Heriot-Watt University, Edinburgh (McCarter *et al*., 1995), is to provide real-time data on the condition of cover concrete and spatial distributions of cover-zone properties (Figure 9). These sensors can be used to monitor moisture movement, chloride ingress and carbonation (McCarter *et al*., 2001). Currently the sensors are being investigated in a joint research project between Heriot-Watt University Edinburgh and Queen's University Belfast to develop performance based specifications, along with the application of the permeation tests developed at Queen's University. Figure 10 shows an exposure site in Scotland where the sensors are being used to investigate the effectiveness of different types of cementitious materials against chloride ion penetration in a marine environment. Also shown in this figure is the full sensor system that allows remote sensing of data as required.

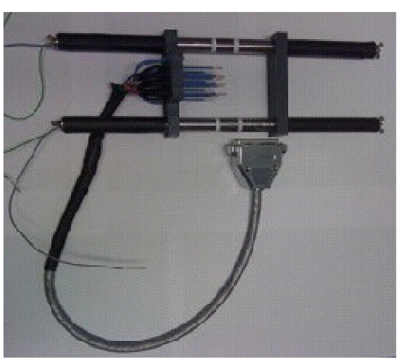


Figure 9. Covercrete Electrode Array and Corrosion Probe

Figure 10. Exposure site in Scotland with remote data collection and solar power units

Exposure sites in China

In collaboration with the Science Bridge partners in China, different exposure sites will be identified in Tianjin, Hangzhou, Xi'An and Chongqing, as highlighted in Figure 11, where the technologies from the UK will be demonstrated. The data thus obtained will be used in service life prediction models.

Figure 11. Location of field exposure sites in China (locations encircled)

'Flexiarch' as a sustainable form of construction for small to medium span bridges

Due to the long service lives exhibited by masonry arch bridges (thousands of years as opposed to several decades for reinforced and prestressed concrete bridges), a novel flexible concrete arch system was developed at Queen's University Belfast (Long *et al*., 2008). This system has the potential to be highly sustainable due to the low or zero amount of steel reinforcement. As the arch system is constructed in the form of a flat pack using a polymer grid reinforcement to carry the self weight during lifting, it is transported also in flat packs, but behaves as a masonry arch once in place (Figure 12). The main advantage of the Flexiarch compared to the more traditional system of masonry arch construction is due to the elimination of centring for erecting the arch. The industrial exploitation of this innovative arch system has been undertaken by Macrete Ireland Ltd. Through activity 2 of the Science Bridge, this novel system will be introduced in China.

Figure 12a. Flat pack "Flexiarch" system brought to site

Figure 12b. Completed arch bridge before covering with backfill.

BEYOND THE SCIENCE BRIDGE

Sustainability of the Science Bridge (short-medium term)

Through opportunities created by Activity 5 of the Science Bridge, both UK and Chinese industries, academia and research centres will have increased participation in knowledge transfer programmes, training and education activities and commercialisation of innovations from both countries. Joint centres are being considered for encouraging wider participation, such as the UK-China Science Bridge Concrete Centre established at Central Research Institute of Building and Construction in Beijing, which will eventually operate on a membership basis.

Education & training (short-medium term)

A considerable number of Chinese construction labourers are unskilled, part-time workers from villages outside the cities and frequently untrained. Reflecting this position, it is recognised in China's 11th five-year plan that the scientific concept of development means China has to change from over-reliance on a cheap labour force, funds and natural resources, to well-educated workers and improvement of science and technology. The aim is a development mode that not only values quantity and speed, but also high quality and energy-efficiency [Yan, 2006].

Against this background, and building on Science Bridge activity areas 3-5, an identified immediate next step is to develop an academic- and industry-focussed education and training model applicable to the Chinese construction industry. The focus of training will be concrete technology, durability and in situ materials' assessment and quality control. As shown in Figure 13, the strategy is to partner with relevant professional and academic organisations in the UK and China to make this possible. The aim is to offer students and practicing professionals, alike, the opportunity to undertake state-of-the-art training packages leading to the attainment of internationally recognised professional qualifications. The aim of this work is help improve the quality of concrete construction in China and, at the same time, enhance the domestic and international aspirations and prospects of participating individuals and companies.

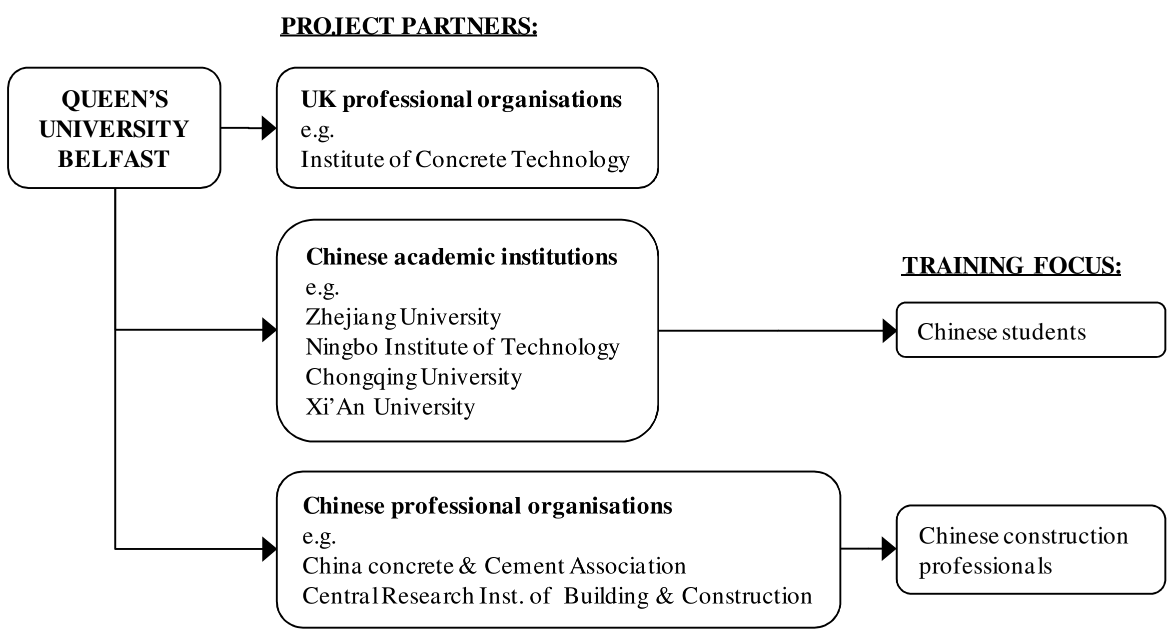


Figure 13. Overview of UK-China Education & Training Model

International influence (long term)

To compliment the UK-China Science Bridge award, Queen's University has made a substantial financial commitment, along with the China Scholarship Council (CSC), to ensure up to 27 PhD bursaries for outstanding Chinese students. Students will join world-class research centres at Queen's University and participate in Science Bridge activities, undertaking research and innovation projects focussing on developing sustainable energy and built environment solutions. With a high proportion of these students predicted to return to China, the long term aim of this investment, and the Science Bridge project in general, is to develop an international network of highly trained professionals with strong links to Queen's University and the UK.

It is predicted that this will assist with the project's overarching aim, which is to benefit the UK from an enhanced uptake of its technology, knowledge and expertise through enhanced business opportunities and strengthened collaborations.

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