DESIGN FOR EARTHQUAKE INDUCED MOVEMENT ON LIFELINES – THE FERRYMEAD BRIDGE EXPERIENCE

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ABSTRACT

Earthquake induced damage to pipelines attached to bridges was a serious problem that resulted from the Christchurch earthquake sequence of 2010 and 2011. Many major pipelines ruptured as a result of vertical movements of up to 500 mm and horizontal movement of up to 1.0 metre towards the rivers.

The provision of flexibility to accommodate major differential movement was a particular concern for the three lifelines crossing the Ferrymead Bridge, two DN 355 PE 100 water-mains and one DN 450 PE 100 sewage rising main. The design brief called for sufficient flexibility to allow for relative movements of up to 0.45 metres vertical (due to liquefaction and settlement) and up to 1.5 metres of movement directly towards the river (due to lateral spreading), all without loss of service. The final design easily allowed for this movement as well as at least 0.5 metres of movement parallel to the river.

The new Ferrymead Bridge was constructed between 2013 and 2015 and its engineering design was awarded a New Zealand Concrete Society infrastructure award – Commendation in 2015 and an ACENZ Innovate NZ silver medal in 2016. Since the earthquake resistant pipeline design was not presented for consideration in this award, this paper has been prepared to document the innovative solution that provided for the design brief parameters.

The design solution, which made full use of the inherent flexibility of polyethylene pipe to accommodate the relative movements with minimal risk of pipe rupture, is described. The critical importance of all aspects of the pipelines was recognised and the rigor applied to QA of all aspects of the pipelines' construction from pipe quality through welding, installation and pressure acceptance testing is included.

KEYWORDS

Earthquake damage, Liquefaction, Lateral spreading, Polyethylene (PE) pipe, Pipe QA, Butt fusion welding, Cranked specials, Pressure acceptance testing

PRESENTER PROFILE

John has had more than 43 years' experience with piped system design, construction and operation. He has been the Opus Technical Principal – Pipeline Materials since 2009. John's close association with plastics pipes goes back to 1974 and earthquake resilience has been one of his main interests since the 1991 Wellington Lifelines Project.

1 INTRODUCTION

The Ferrymead Bridge carries in excess of 30,000 motor vehicles per day as well as the water supply, sewerage, power and telecommunications lifelines which service the Christchurch suburbs of Mount Pleasant, Moncks Spur, Redcliffs, Sumner and Scarborough.

Located at the mouth of the Heathcote River where it flows into the Avon/Heathcote estuary, the site is underlain by loose to medium density, liquefiable, fine, sandy estuarine soils which vary in depth from 7 metres - 21 metres[1]. The 1997 Christchurch Lifelines study highlighted the vulnerability of the then existing (1967) Ferrymead Bridge to earthquakes and liquefaction damage[2]. This Lifelines study led to a project to strengthen and widen the existing bridge. Construction works commenced one week prior to the 4 September 2010 earthquake event. The bridge suffered minimal damage from this September earthquake event which had an epicentre located approximately 40 km away, at Greendale.

However, the 22 February 2011 earthquake had a focal depth of just 5 km with an epicentre that was located less than 2 km from this Bridge. The ground acceleration at the Bridge, both vertical and horizontal, is likely to have been 1 g or more[2]. This event caused substantial damage to the bridge as well as the partly completed bridge strengthening and widening works. The damage was largely caused by the effects of liquefaction and the associated lateral spreading.

2 WATER SUPPLY AND SEWAGE LIFELINES

The water supply and sewage lifelines crossing this bridge are as essential to the wellbeing of residents as vehicular access and their resilience to seismic induced movement is of paramount importance. Differential movement between the river banks and the bridge had been recognised (since the 1997 Lifelines Study[3]) as a critical design issue which required these pipelines to be able to accommodate significant movement without loss of service even if subsidence resulted in lack of vehicular access.

The fact that this was a new bridge that had been specifically designed for earthquake resilience made the installation more straight-forward than would be the case for a retro-fit on an existing bridge. However, the design principles established for this project can be applied to most bridges that carry lifeline services.

2.1 THE 2010 DESIGN REQUIREMENTS

For the 2010 (pre-earthquake) bridge strengthening and widening upgrade, the water supply and sewerage lifelines were intended to accommodate differential movement of not more than 200 mm in any direction. These piped lifelines were then to be two DN 315 PE 100 water mains and a DN 400 sewage pressure main. Polyethylene (PE) pipes of PE 100 resin, complying with AS/NZS 4130 were considered to be flexible and resilient enough to provide for the design movement with only moderate “stretching” at the bridge approaches and “snaking” between hanger supports under the bridge. PE pipes end-load bearing joints were also considered to contribute greatly to their earthquake resilience.

Pipes with a nominal pressure rating (PN) of PN 12.5 had been chosen for the water mains on the basis of their higher resistance to kinking than the optional PN 10 pipes (which would have been satisfactory for the current operating pressures). The use of PN 12.5 pipe would allow for possible increases in capacity/pressure in future. While the sewage pressure main only operates under a few metres head (and drains out after each pumping cycle) PN 12.5 pipe was also chosen for its higher resistance to kinking.

Authors note: Some low pressure class pipelines were temporarily operated at, or in some cases, >25% above their rated pressure during the recovery phase after the February and June earthquakes in order to maintain adequate water supply to some areas of the city[4].

The 2011 earthquakes (22 February and 13 June) showed that the differential movement could be significantly greater than the maximum 200 mm provided for in the 2010 upgrade design. This demanded a re-think to maximize the chances of the lifelines surviving another significant seismic event. The proposed pipe sizes were also increased in 2012, as part of the post-quake temporary works, to two DN 355 PN 12.5 PE 100 water mains and a DN 450 PN 12.5 PE 100 sewage pressure main.

2.2 THE 2013 DESIGN REQUIREMENTS

The 2013 design required these pipelines to survive an event that could cause movement of the non-liquefiable crust above the liquefiable estuarine sands of 750 mm – 1500 mm horizontally (expected to be perpendicular to the river), accompanied by up to 450 mm of vertical drop as observed at some other bridges across the Avon River. This movement would be largely independent of the bridge structure which was not expected to move more than 150 mm - 200 mm in an earthquake event, due to the innovative design of the abutments and piles[5].

3 OPTIONS CONSIDERED

By 2013, it was becoming accepted that attempting to design any structure or service to resist all possible seismic forces was likely to be futile. The best that could be done was to build it flexible enough to resist most foreseeable forces and affordably fixable, should the event exceed the design.

3.1 PIPE MATERIALS OPTIONS

The Opus Pipe Materials Options and Seismic Report for the three lifelines crossing the Ferrymead Bridge (prepared in 2010) considered a number of pipe material options. This report was reviewed and updated in October 2013 to provide options to accommodate the increased differential movements that resulted from the 2011 earthquake[5].

The Pipe materials options considered in the 2010 report included:

- PE 100 (the chosen option)
- Polyvinylchloride (PVC)
- Ductile Iron (DI)
- Stainless Steel (S/S)
- Concrete-lined Steel (CLS)

Only the PE pipe option was considered to be capable of providing sufficient flexibility to allow for the designed movement within a manageable area. Lateral spreading towards the river would mean that the pipe could be required to "stretch" at the approaches to the bridge and "compress" under the bridge. The design lateral spreading movement of 1.5 metres towards the river would be unlikely to all be transferred into the approaching pipes as there would be "slipping" within the bedding material over a length of at least 30 metres until skin friction on the PE pipe become dominant. The amount of "stretching" of the buried pipe leading to the bridge abutment could be accommodated by less than 5% elongation of the PE pipe.

The bridge design intent was to reduce the lateral loads on the structure that would result from liquefaction and lateral spreading. To achieve this, the abutment piles, where lateral spread loads are unavoidable, were designed to be just three in number, and slender, with a diameter of only 1.1 m, to reduce the area of the piles that would attract the lateral spreading loads from the liquefied ground.

The bridge has two main spans with a strong central pier in the middle of the river. The placement of the central pier will ensure that it is unaffected by lateral spreading of either river bank. Short land-spans with a cavity behind the main abutments are provided at each end of the bridge to minimise the lateral spread loads from the surface crust above the underlying liquefiable soils. These short-land spans are designed to be destroyed in a major event and to be quickly restored afterwards.

A highly flexible configuration of the piped services was necessary to ensure that the vertical and horizontal movements could be accommodated without damage to the pipes. The cavity behind the bridge abutments provides an area for free movement of the water supply and sewage lifelines as well as the other communication and power supply services

Some of the compression of the pipes suspended under the bridge could also be accommodated by "snaking" of the pipe between the pipe hangers and by bending of the hangers if the compression type movement was large enough.

3.2 OPTIONS TO PROVIDE FOR MAJOR DIFFERENTIAL MOVEMENT

The options considered in the updated 2013 report for these lifelines were:

- Option A. A "straight" section of pipe from the bridge approaches and under the bridge deck (as was intended in the 2010 design). *This was discounted as the pipe would not be able to accommodate the design movement without severe buckling, stretching and kinking.*

- Option B. Create a horizontal "crank" in the pipelines each side of the bridge. A pair of PE 100 90° swept bends joined together with a length of pipe to form a "crank" that would absorb the movement without buckling or kinking of the pipes. *(The chosen option).*
- Option C. Create a similar horizontal "crank" but using flanged DI 90° bends in conjunction with a PE pipe connection to form the "crank". The DI bends would have a significantly tighter radius than the formed PE bends but would reduce the flexibility of the cranks and would have a higher risk of kinking the PE pipe unless the length of the connection between the DI bends was increased. (*The alternative option if there was a space constraint).*

Other options that were considered and rejected were:

- DI earthquake joint systems, e.g. Force balanced Flex-tend or the American Pipe Earthquake joint. The American pipe earthquake joint did not have sufficient movement for our purposes. The Flex-tend units could have been used in conjunction with flanged DI elbows and a 5 metre length of PE pipe to create a "crank" to allow for the design movement. The cost of this system would have been substantially greater than the chosen option. Maintenance/replacement of these mechanical joints over a design pipeline life of more than 100 years was also likely to be an issue in the future.
- Rubber bellows joints. Rubber bellows joints were not considered for the water mains as they have had a variable reputation in service and the rubber would deteriorate requiring several replacements during the design life of the pipelines. They would also have needed to be used in conjunction with DI bends.
- Steel pipes jointed with Victaulic couplers to form "cranks" (seismic separation assemblies) as used in large fire sprinkler systems. These assemblies involve the use of steel pipe sections, steel 90° elbows and Victaulic couplers. The complexity of the overall installation and the size needed to accommodate the design movement, especially for the DN 450 pipeline, made these unwieldly and costly.

Pipes of PE 100 complying with AS/NZS 4130 will stretch more than 300% before failure occurs and a small amount of "stretching" would be unlikely to cause short term failure of the pipe. Swept 90° bends were chosen as the preferred option for the "cranks". At the time (2013) the accepted guidelines for de-rating the operating pressure for PE pipe fittings (PIPA POP 006 issue 5.01) required formed "sweep" bends to be de-rated by a factor of 0.8. This meant that bends formed from PN 12.5 PE pipe would have a rated pressure of PN 10. In order to ensure that these bends would have the same pressure rating as the PN 12.5 pipe, it was necessary to have them formed from PN 16 PE 100 pipe.

Authors note: the latest PIPA POP 006 issue 5.2 does not require any pressure de-rating of formed bends, provided the minimum wall thickness (on the outside of the bend) complies with the requirements of AS/NZS 4130.

4 FINAL DESIGN

4.1 BACKGROUND

PE 100 pipes have been the pipes of choice for much of the Christchurch Earthquake recovery and re-build pressure pipes. This is due largely to their flexibility and ability to accommodate differential movement (when allowed to move and bend freely) and their end-load resisting, butt fused joints.

Analyzing the structural performance of the preferred cranked specials would be quite difficult and after consideration it was decided that building a physical "scale" model of the cranked specials of one side of the bridge would provide assurance that the design could accommodate the designed differential movement and resist possible super-design movement as well as repetitive flexing in a ground shaking event.

The scale model was constructed from DN 25 PN 12.5 PE 100 pipe (for the two DN 355 water mains) and DN 32 PN 12.5 PE 100 pipe for the DN 450 sewage pressure main. These two pipe sizes closely approximated the relative diameters of the real pipes and were very close to a scale of 1:14. Using DN 32 pipe and DN 40 pipe (a model scale of 1:11) was considered but was not followed through due to the additional physical effort that would be required to deflect the cranks and the increased size of the model.

The model was constructed by the author (using back-yard butt welding techniques dating back to the early 1960's) to make the double mitre segmented 90°elbows. The model pipe cranks were then mounted on two timber planks to ensure that they moved in unison and demonstrated to the Water and Waste Manager at Christchurch City Council for approval to proceed. There were a number of interesting learnings that came out of that demonstration:

- The cranks flexed and accommodated the "scale" design compound movements easily without kinking or buckling.
- They also accommodated repetitive movements without damage
- However, when the design movement was exceeded by approximately 25%, one of the mitred welds in the 90°elbows broke by brittle fracture.
- The demonstration satisfied The Water and Waste Manager
- However, it showed the potential risks posed by poor welding. As a result, the decision was made to use formed 90° bends to eliminate the mitred welds in a segmented or "lobster-back" bend.

4.2 THE ADOPTED DESIGN

The final design adopted is shown as a pictorial and plan view in Figures 1 and 2. This system is mirrored on each side of the river and as demonstrated (by physical model) is capable of providing for the desired movement without damage to the pipes. It would be capable of accommodating at least double the design requirement of 450 mm of vertical "drop" by simple torsion (twisting) of the pipes.

A pictorial view of the installation on the City side of the bridge is shown in Figure 1. This view shows the cranks in a partly "deflected" condition with lateral spreading movement horizontally towards the river of approximately 500 mm.

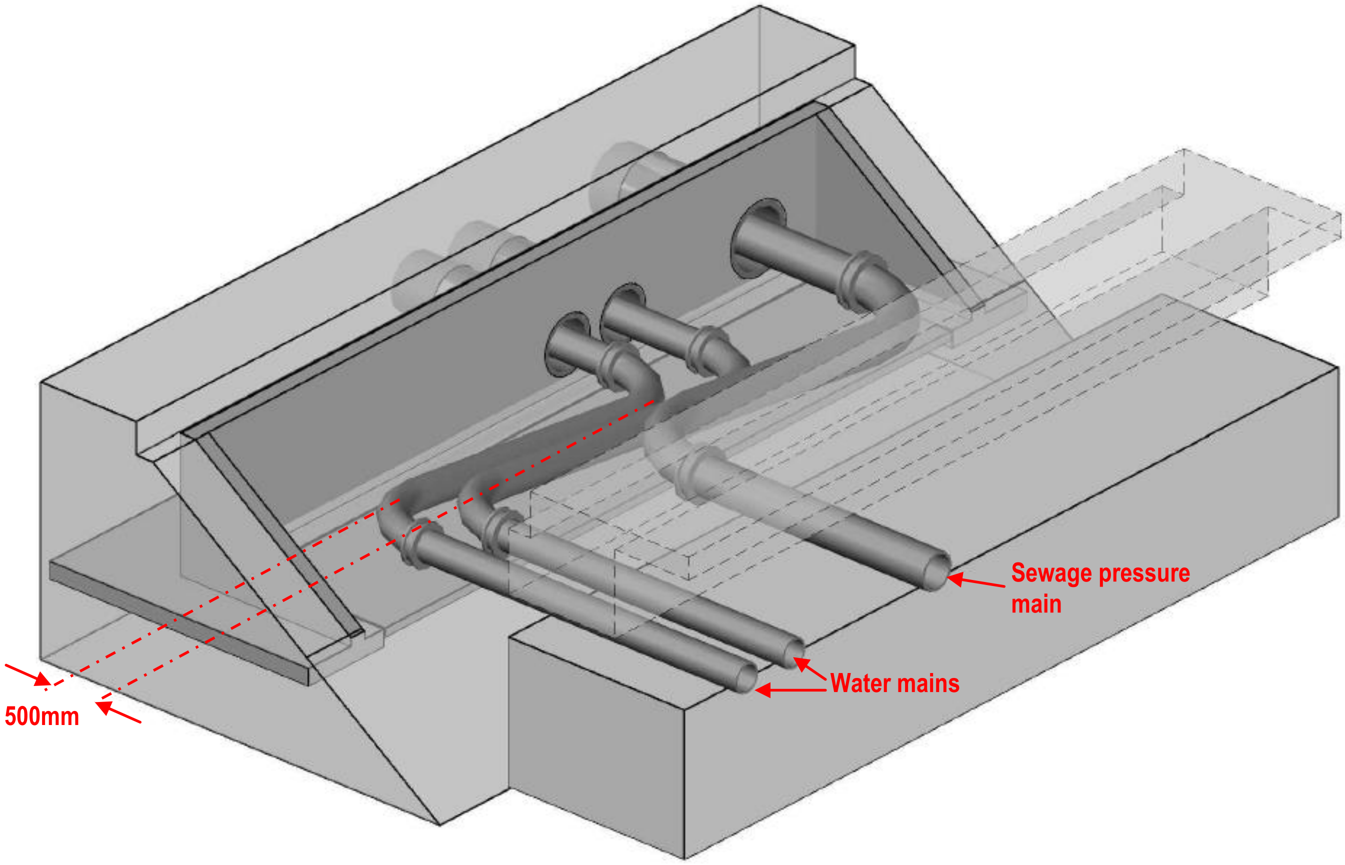

Figure 1: Pictorial view of the cranked bends on the City side of the river.

A plan view of the installation on the City side of the bridge is shown in Figure 2. This view shows the cranks in an “un-deflected” condition i.e. as constructed. The pipe ducts through the retaining wall (left side of the drawing), allowed the pipes room to move vertically and laterally to provide additional flexibility.

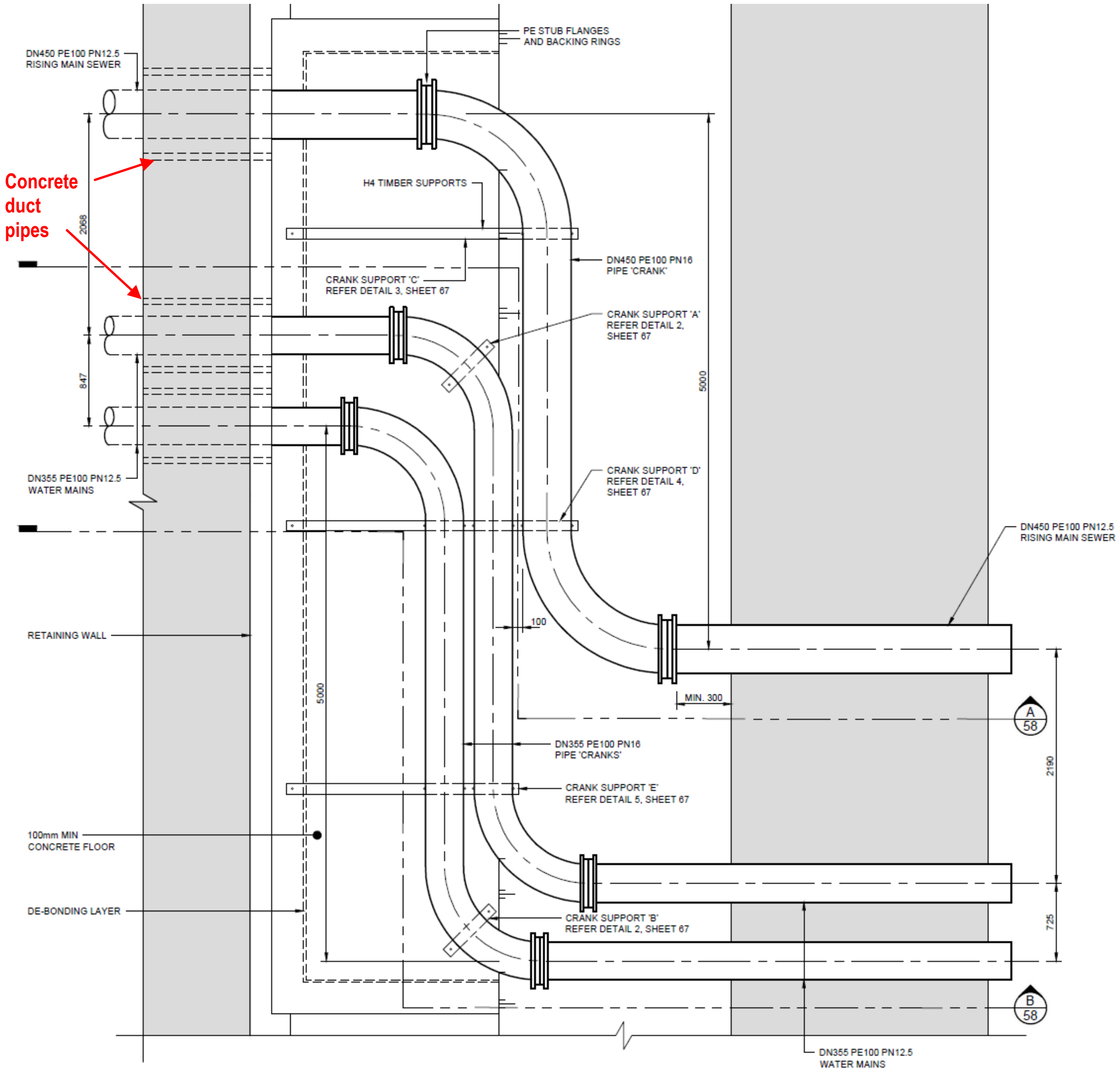

Figure 2: Plan view of the cranked bends on the City side of the river

Photograph 1 shows the “cranks” as installed in the cavity beneath the land-span on the City side of the bridge. The crank cavity was made bird-proof by using stainless steel mesh between the pipe cap and the bridge deck (see Photograph 2) which also made it difficult for vandals or homeless people to frequent the area and potentially cause damage to the PE pipes or air valves. The only access to the two cavities is through a cast iron manhole cover, one on each side of the bridge. Entry into these cavities requires a manhole lifter and a ladder.

Photograph 2 shows part of the two DN 355 water main cranks, the air valves and the stainless steel mesh (bird and vandal proofing) on the Sumner (eastern) side of the bridge.

Photograph 1: View of the installed "cranked" specials on the City side of the river. The DN 450 sewage pressure main crank has been extruded from black PN 16 PE 100 resin.

Photograph 2: View of the air valves on the DN 355 water mains on the Sumner side of the river. The stainless steel mesh prevents unauthorized access to the cavity area.

5 CONSTRUCTION

The fractured mitred weld on the demonstration model served as a reminder of the possible risk posed by using mitred 90° bends with six welded segments that would be subjected to severe bending in the design earthquake. Every aspect of pipeline construction for lifelines needs careful attention and the water mains and sewage pressure main of this project have been given the most thorough auditing and appraisal of any similar project that I am aware of to date.

The following sections show in detail the work that was carried out to minimise the risks associated with pipe material, butt fusion, construction and pressure acceptance issues.

5.1 PE PIPES AND CRANKED SPECIALS

PE pipes complying with AS/NZS 4130 were specified for this project. The manufacturers QA records were requested and these were thoroughly vetted. The PE resin manufacturer's certificates of analysis for the PE 100 resin used were also obtained. In this case, the PE resin for all of the pipes used , including the PN 16 pipes for the formed cranks was sourced from a PE 100+ resin manufacturer with a good reputation around the world (Borouge HE 3490 LS).

Independent testing of samples cut from the water main and sewer pipes was carried out by ExcelPlas, an accredited laboratory in Australia. The tests were for oxygen induction time (OIT) and melt flow rate (MFR) to give the asset owner confidence that the pipes supplied were extruded from the resin claimed.

The pipes supplied for this project had a coloured jacket, blue for the water mains and cream for the sewage pressure main (as required by Christchurch City Council. The PE compound used for the coloured jackets is known as a striping compound because it is usually used for coloured stripes on pipes as opposed to a full jacket. The striping compound resin details were also supplied and reviewed. The compatibility of the striping compound was also confirmed by EF coupler tests.

Authors note: On another major pipeline in the Christchurch rebuild works, a striping compound was used that was claimed to be PE 100 but while butt fusion joints were not compromised, the pipes could not be successfully welded with EF couplers. No factory test EF welds were carried out (or requested) so the problem was not found until EF joints started failing under pressure testing, sometimes even when the pipe was being filled.

The dimensional compliance (with AS/NZS 4130) was checked on a number of pipes during construction and some ductility tests were also carried out on some pipe samples. The pipes were all dimensionally compliant and the ductility tests showed that the pipe was particularly ductile. The parent pipe specimens for each of the weld tensile tests also showed that the pipe had appropriate tensile strength and fractured in a ductile manner

Pipes used for the cranked specials (PN 16, SDR 11 PE 100) were produced from some of the same resin batch as was used for the PN 12.5, SDR 13.6 pipes used for the water mains and the sewage pressure main.

5.2 PE PIPE BUTT AND EF WELDING

Butt fusion welding of PE pipes generally has a very good track record world-wide and the established welding equipment, procedures and QA testing give as much assurance of weld quality as can be realistically achieved.

The pipe manufacturer for all of the DN 355 and DN 450 pipes (Pentair) also conducted weld tests on pipes of the same batches as the supplied pipes. The tensile test results for these welds were also reviewed. The tensile test results showed that correctly-conducted butt welding of these pipes could produce strong, ductile welds.

Only experienced and registered polyethylene pipe welders that were on the Stronger Christchurch Infrastructure Rebuild Team (SCIRT) approved welders list were used for this project. Each welding operative produced pre-construction and construction welds on the DN 355 water mains and the DN 450 sewage pressure main. The results of the tensile tests on these test welds confirmed that the total system, the pipes, the welding equipment, the weld parameters and the welding operatives produced quality welds that were strong and ductile.

All tensile tests on the welds were carried out on Type B test coupons and to the test parameters of ISO 13953, the recognised testing standard used for all of the Christchurch rebuild works.

5.3 ELECTROFUSION FITTINGS

While no EF coupler joints were allowed on the water mains, Pentair's EF test results showed that the striping compound was compatible and gave assurance that it would be possible to use EF couplers for repair works in the future, should this ever be necessary.

It was necessary to use two EF couplers on the sewage pressure main as a construction expedient to allow for installation in stages across the road and maintain vehicle access. These two joints were located using GPS so that it would be possible to locate them in future from the as-built drawings. As this pressure sewer is only operating at very low pressure, any risk of failure of EF couplers was considered to be acceptable.

Two EF saddle fittings were needed for the air valves on the water mains, see Photograph 2. While these types of fittings also present a significant risk of failure, it was decided that provided a test saddle weld showed acceptable ductility and the welding procedure for the two saddles in Photograph 2 was observed to verify the preparation work (the effectiveness and depth of scraping to remove the oxidized layer) and the fusion process, any risk of failure would be low and would be acceptable. Also, there was assess for repairs and the second water main provided an alternative supply.

5.4 PRESSURE ACCEPTANCE TESTING

Pressure testing of PE pipelines can be difficult and especially so on exposed pipelines (these three lifelines are suspended under the bridge for approximately 50% of their total length).

The pressure acceptance test method used for these critical lifelines was the M5 (constant pressure) test from AS/NZS 2566.2. AS/NZS 2566.2 does not prescribe the test method in detail, nor does it highlight the criticality of the pressures and water volumes added in the evaluation of test results. In order to address this matter, specialised pressure acceptance test training was carried out by the author, as part of the SCIRT led earthquake rebuild works. The criticality of pressure logging (at 5 second intervals or less) during the test and the measurement of the volume of water added during the test was highlighted for a successful M5 pressure test. This training led to a small number of contractors being registered as certified pressure testing contractors for PE pipelines. Two different (registered) contractors were used at various times for pressure testing these three PE pipelines.

Not surprisingly, one of these pressure tests (of the DN 450 sewage pressure main) was seriously affected by temperature change and the test was rejected by CCC as it did not meet the M5 test pass criteria. The test was repeated a month later and was carried out during relatively stable temperature conditions.

6 CONCLUSIONS

Seismic movement, liquefaction and lateral spreading in the Christchurch earthquakes of 2011 caused pipelines to fracture at the approaches to many bridges across the Avon and Heathcote Rivers. It was necessary to design a pipe system at the bridge abutment areas that would accommodate the amount of movement that could be expected in a major earthquake event without being damaged even though vehicular access across the bridges could be disrupted for a time while temporary repairs to the land-bridge approaches is carried out.

The inherent flexibility of PE 100 pipes and their end-load bearing, butt fusion joints has allowed a relatively simple and affordable design approach to accommodate significant differential movement while still maintaining the pipeline integrity.

By creating cranked "specials" and providing a cavity which allows the pipes and cranks to move freely, significant differential movement could be accommodated without pipe damage, as was verified by a physical model.

This relatively simple design concept could be adapted and used at other bridge crossings where significant differential movement is expected in a seismic event.

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