Synchronous Test Platform for Functionality Verification and Structural Capacity Evaluation of Subsea Equipment

http://dx.doi.org/10.3991/ijoe.v9iS6.2808

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***Abstract*—In order to verify the functionality and evaluate the structural capacity for subsea equipment simultaneously, a synchronous test platform was established, which consists of the test setup part and the data measurements part. Based on this platform, a test was conducted on a subsea wellhead connector to illustrate the test process and principle. A numerical calculation using a developed three-dimensional finite element model was performed to compare with the test data. The results of numerical calculation and test have great good agreements. For further application, this synchronous test platform could be used for performance study of the subsea equipment under cyclic load and variable load. This paper is also bringing promotional values for other subsea device with similar and even more complex working condition.**

***Index Terms*—subsea equipment, synchronous test platform, functionality, structural capacity, hydrostatic pressure**

I. INTRODUCTION

Subsea equipment is commonly used for deepwater oil and gas exploration and development, such as subsea Xmas tree, subsea wellhead, and subsea blowout preventer (BOP). Under the water, the external hydrostatic pressure and the internal well pressure affect its functionality and the structural capacity simultaneously. With the increase of water depth, this effect is more significant, and even result in leakage, buckling, and collapse [1, 2].

Several studies have been performed to analyze the impact of the underwater environment on the subsea equipment. Ali *et al.* [3] introduced the technical challenges of external hydrostatic pressure for new deepwater valve actuator and presented design and analysis methods for developing and qualifying. Skeels *et al.* [4] discussed the design method of subsea intervention equipment taking into account the water depth for the design working pressure. Montgomery *et al.* [5] carried out a failure analysis of the subsea BOP experiences external hydrostatic pressure and well pressure simultaneously. Damgaard *et al.* [6] built a set of physical model experiments to determine the expected pull-in loads for jumper configurations subjected to combinations of lateral and longitudinal forces. Shaughnessy *et al.* [7] analyzed the problems of ultra-deepwater drilling, and pointed out that the test of the subsea emergency disconnect system should be considered to ensure the functionality of equipment under the water. Cai *et al.* [8] studied the load and resistance factor design of pressure vessel for subsea blowout preventers. But these previous works have left issues unresolved: (1) no enough experimental work was embedded in the calculation and analysis since the test data is the foundation towards the design and application of the subsea equipment; (2) the external hydrostatic pressure test and the functionality verification test were not conducted simultaneously [9]. In order to improve the reliability and safety of the subsea equipment during the installation, production, and maintenance, a synchronous test that simulates the real seabed environment and investigate their service behavior is necessary.

The work presented in this paper commenced with a detailed introduction of a synchronous test platform for functionality verification and structural capacity evaluation of the subsea equipment. The test setup part and data measurements part of the platform were described. A test was then conducted on a subsea wellhead connector to illustrate the test process and principle. Meanwhile, a numerical calculation based on finite element analysis (FEA) was performed to compare with the test data. Furthermore, this article has greater promotional value for other subsea device with similar and even more complex working condition.

II. SYNCHRONOUS TEST PLATFORM DESIGN

A. Test Setup

An overview of the synchronous test platform with inside subsea equipment is shown in Fig. 1. The hydrostatic pressure chamber is placed on the ground to withstand water pressure for simulating the seabed environment. Its total volume is about 18m^3, which can meet the room requirement for most subsea device, such as subsea control module, subsea connector. With 15MPa rated pressure, the maximum seawater depths simulated by the test setup is about 1500m. For the purpose to drive and load the subsea equipment, there are a maximum of sixteen 3-in penetrations for electrical, hydraulic and pneumatic lines to connect the outer control facilities and the inner devices. One can obviously see two flow paths, namely, outer flow path indicated by blue color and the inner flow path marked by purple color. The water in both flow paths are transported by the electrically driven pumps. The two pumps are centrifugal-type water pumps with a rated power of 20 hp. The outer flow path provides the external hydrostatic pressure in the chamber for subsea equipment. A 5-in steel pipe is used to connect the inlet, outlet and the water supply. Two valves are installed to control the flow rate. This flow path can pressurize the chamber to a maximum rate of 2 Mpa per minute. Mean-

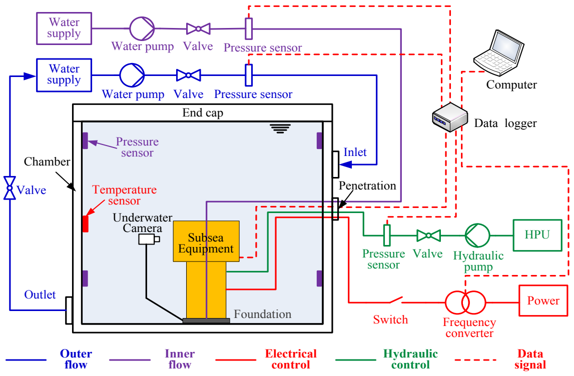

Figure 1. Layout of the synchronous test platform

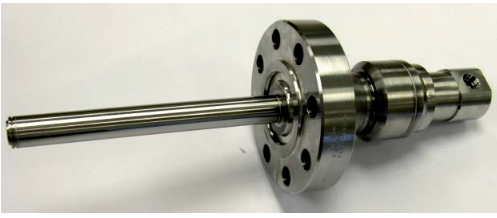

Figure 2. GE PTX400 pressure transducer

while, the inner flow path consists of a water pump, a hose and a valve. By a 3-in Parker Polyflex™ hose through the penetration, an internal pressure up to 180MPa could be applied on the subsea equipment. In this synchronous test platform, the subsea equipment could be changed easily by opening the end cap. With hydraulic or electrical drive, the subsea equipment can carry out the same functionality and motion as they are used on seabed. The hydraulic control assembly consists of a hydraulic power unit (HPU), a hydraulic pump and a valve, while the electrical control assembly is made up of a power, a frequency converter and a switch. Moreover, a foundation welded to the bottom of chamber is used to fix the subsea equipment with bolts. For the purpose to visually verify the functionality and the performance of subsea equipment, an underwater camera is placed inside the chamber. It will be capable of operating under the maximum hydrostatic pressure.

B. Data Measurements

A temperature and four pressure transducers are located on the inner surface of the chamber to monitor water temperature and external hydrostatic pressure respectively. To simulate a relatively stable seabed environment, the errors of pressure and temperature are controlled in ±1MPa and ±1℃. In the internal cavity of subsea equipment, a GE PTX400 pressure transducer (shown in Fig. 2) is used to survey the internal pressure and judge the failure status, such as a leakage condition. Strain gauges on the critical position are used to achieve the behavior and response of the subsea equipment during test. The signals of temperature, pressure and strain are monitored and recorded by a HYDAC™ data logger which can obtain 30 groups data simultaneously (see Fig. 3). A computer receives the test data from the data logger by a VB programmed data acquisition software. Its visual control interface is shown in Fig. 4. The real-time test data are shown in curves within the small windows. Ultimately, the test results are obtained and recorded by the computer automatically.

Figure 3. HYDAC™ data logger

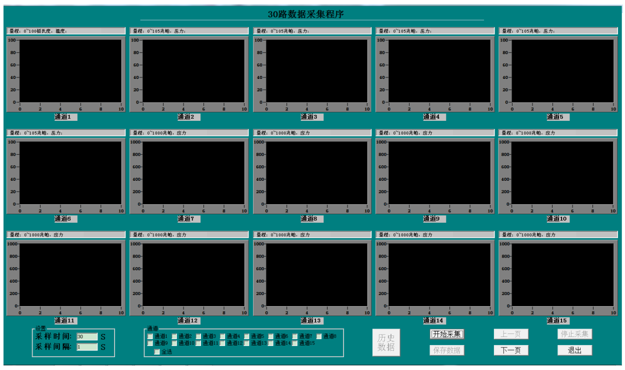

Figure 4. The data acquisition software interface

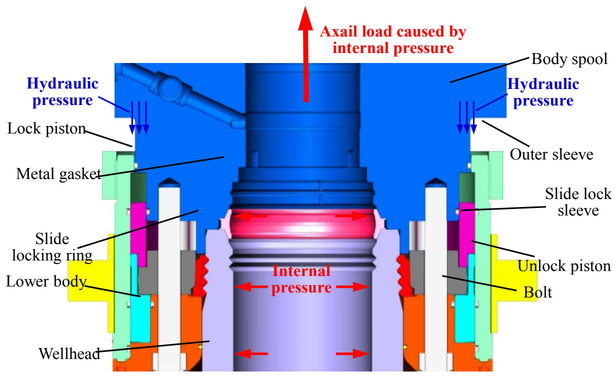

Figure 5. Main components and loads of a subsea wellhead connector

C. subsea equipment for test

In order to illustrate the test process and principle conveniently, a subsea wellhead connector was adopted as an example. The subsea wellhead connector provides pressure integrity and a rigid structural connection between the subsea Xmas tree and the wellhead. Its major components are shown in Fig. 5. The connector is locked by applying hydraulic pressure above the lock piston. This generates a downward locking force which is transferred to the slide lock sleeve. As the slide lock sleeve travels down, the split lock ring is compressed radially. Then the connector locks to the wellhead by the split lock ring, which forces the lower body down and generates a stretch in the bolts. The metal gasket is the primary method of sealing between the wellhead and the connector. The stretch in the bolt ultimately results in a compression between the body spool and the wellhead to preload the metal gasket.

In practice, the connector is subjected to a difference between the external hydrostatic pressure and the internal well pressure. This load generates an axial load with a sealing diameter (the largest diameter of the metal gasket recess exposed to internal pressure) (see Fig. 8). In this study, the connector works in 1000m seawater depth with a rated working pressure of 105MPa. Its main dimensions are 1296mm outside diameter, 913mm height of the housing, 689mm inside diameter, 76.2mm bolt diameter. The purpose of the test is to verify the functionality of locking, sealing and evaluate the structural capacity of the connector under combination of external hydrostatic and internal pressure. In the synchronous test, a test stump bolted to the foundation has the same locking profile to split lock ring as wellhead, and maintains the internal pressure with the internal cavity. Strain gauges (the red nodes in Fig. 6) are located on the split lock ring and each bolt which govern the structural capacity of the connector. A GE PTX400 pressure transducer installed in the internal cavity is used to monitor the internal pressure and sealing performance. In order to verify the locking functionality, two indicator rods are connected to the top of the slide lock sleeve and extended out of the body spool. When the slide lock sleeve moves down together with the piston, the indicator rods will show their stroke. This process will be observed by the underwater camera, as shown in Fig. 7.

During the test, the connector was loosely positioned on the test stump and the lower body was pushed up into firm contact with the split lock ring (see Fig.6). After the connector was locked on by applying hydraulic pressure, the chamber and the internal cavity was filled with water to generate the external hydrostatic pressure and internal pressure respectively.

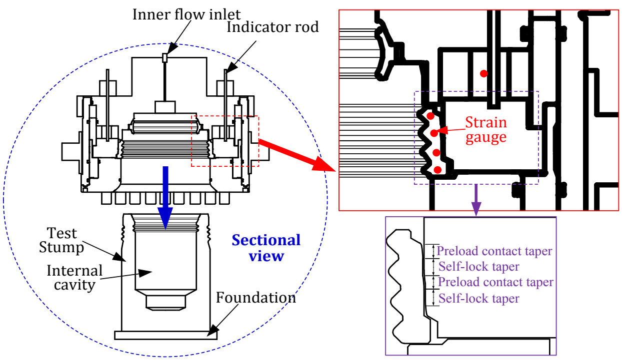

Figure 6. A subsea wellhead connector for test

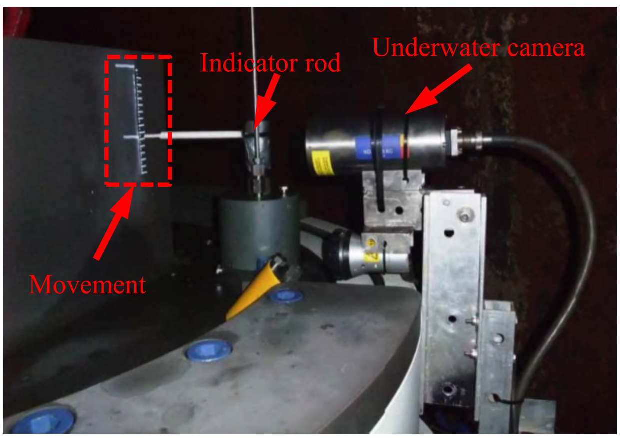

Figure 7. Video Camera setup observing indicator rod

III. NUMERICAL METHOD

A numerical calculation based on FEA was performed so as to compare with the test data. Over the past years, the finite element model (FEM) used to evaluate the structural capacity of subsea wellhead connector was constructed from two-dimensional axisymmetric elements, which cannot precisely simulate the non-axisymmetric behavior of components [10]. Therefore, a three-dimensional half (180° segment) model was developed using MSC.Marc [11], as shown in Fig. 8. Elements used are MSC.Marc number 7 which are eight node hexahedral solid elements for all components except the split lock ring. Material properties are isotropic for these components. The split lock ring is swept out 180° to prevent edge slide-off during locking, and is added with beam elements 52 to simulate correct hoop behavior. As the lock ring is not continuous in the hoop direction, orthotropic material properties are used to model its segmented nature. Young's modulus and Poisson's ratio are assigned small values in the hoop direction. The fixed support boundary condition is used at the bottom of wellhead. Holding the wellhead via a surface is achieved using the MSC.Marc glue option. The metal gasket is linked to the ground through a spring with close to zero stiffness. The contact model used is based on a direct constraint formulation. The external and internal pressure are modeled with face loads acting at the faces of the external and internal diameter of the wellhead, metal gasket and the body spool respectively. The axial load is applied on a reference node coupled with the surface glued to the body spool and then transferred to the connector. For model stability purposes, locking hydraulic pressure is modeled using displacements load on the top of the lock piston. An Intel Xeon TM (2.40 GHz) workstation computer is used to carry out the FEA.

IV. RESULTS AND ANALYSIS

During the connector locking down, the external and internal pressure have the same value of 10MPa. In the FEA, a 98.3mm displacement load was applied based on the geometry of connector. With the lock piston being pushed down, the bolt stress increases gradually, as shown in Fig. 9. The surface between the locking sleeve and the split lock ring has 5° preload contact tapers to generate preload and 0° self-lock tapers to lock the split lock ring in place (shown in Fig. 6). When the lock piston

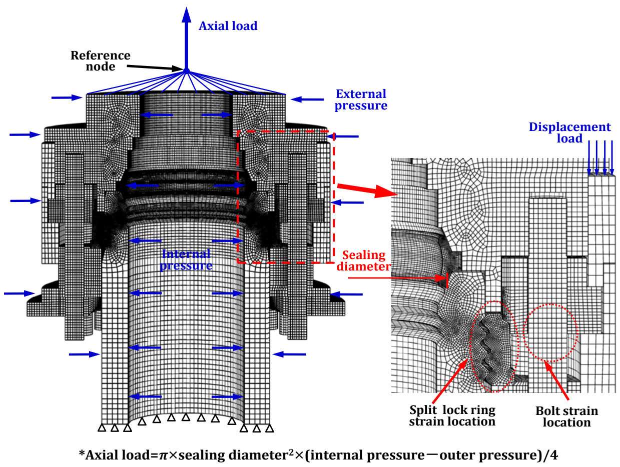

Figure 8. Three-dimensional half model of connector

stroke is between 25 and 35mm and again between 65~75mm, there is a clear increase of both stress where the preload contact tapers. The bolt stress caused by the full lock piston stroke is 321.7MPa, and is called the bolt prestress. The FEA hydraulic pressure is calculated using the lock piston face area and the reaction load on the lock piston. In the test, an increasing hydraulic pressure up to 34.5MPa is applied directly, which results in a 97.9mm lock piston stroke and a 330.5MPa bolt prestress. The hydraulic pressure curves and the bolt stress curves have the similar trend. With bolt prestress, the preload of FEA and test caused by 18 bolts are 26.4MN and 27.1MN respectively.

After locking down, the connector was applied an increasing internal pressure up to the test pressure of 160 MPa (which is over 1.5 times of the rated working pressure) [12]. Fig.10 shows the test and FEA results of the connector structural capacity. The prestress failure point is defined as the breaking off of the bolt stress curve. At this point, the FEA shows a 137.2MPa structural capacity, while the test shows a 140.8MPa structural capacity. With a 521.6 mm sealing diameter, the axial loads caused by the two structural capacity are 29.3MN and 30.1MN respectively, and are higher than the bolt preloads. It is due to that the internal pressure generates a radial force, which improves the structural capacity of the connector. When the internal pressure increases continuously, the axial load gradually neutralizes the bolt preload to be the main factor to influence the structural behavior of the connector. The effect of radial force is no longer evident.

In Fig.11, the FEA shows an obvious increase of gasket contact force with the growing internal pressure. When the internal pressure reaches 160MPa, the lowest gasket contact force is about 8.2kN/mm, which indicates that the gasket contact load will never drop below the leakage failure criterion of 200N/mm [13]. Due to the warping deformation of the metal gasket, the upper surface load is greater than the lower surface load. During the test, no leakage was found, even internal pressure caused a preload failure of the connector. According to the above results, it can be conclude that the sealing performance of the connector is very well.

As shown in Fig. 12, the 160MPa internal pressure leads the plastic strain for spilt lock ring to the maximum value of 2.05%. In this loading case, the maximum plastic strain of the test data increases from 0.73% to 1.98%. Based on the failure criteria of 5% local plastic strain [13], the FEA and test indicate that there is still much elastic strain energy in the connector.

In Table 1, the FEA results are compared with the test data. For the functionality verification, the maximum hydraulic pressure has the maximum relative error of -3.77% for the numerical results. And for the structural capacity evaluation, the maximum relative error of +4.49% belongs

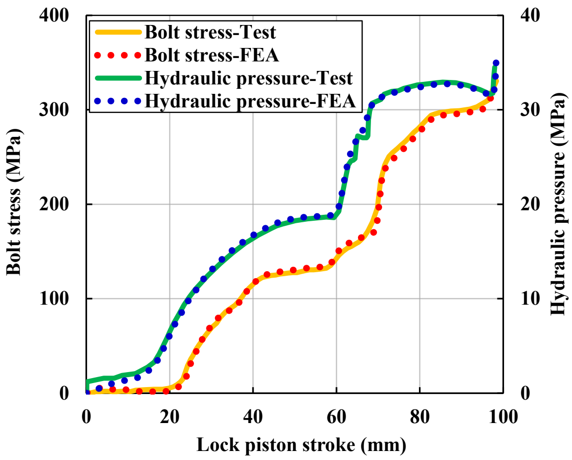

Figure 9. Lock piston stroke vs. bolt stress and hydraulic pressure

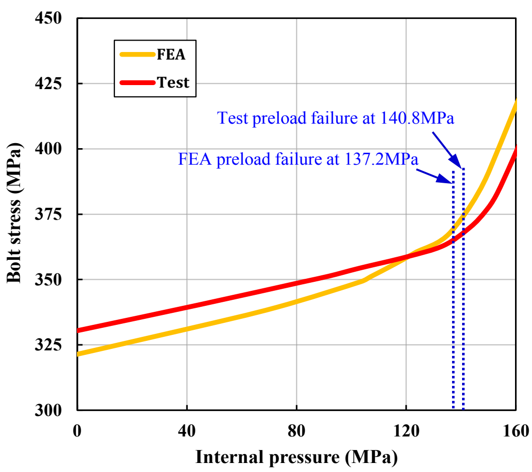

Figure 10. Internal pressure vs. bolt stress

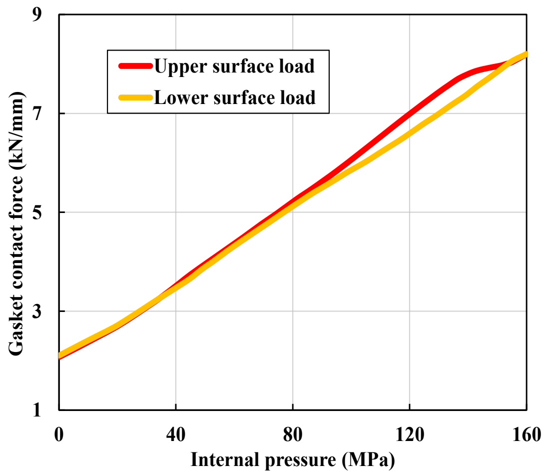

Figure 11. Internal pressure vs. gasket contact force

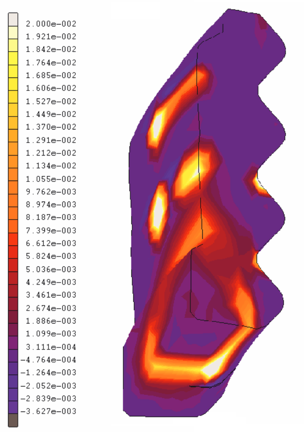

Figure 12. Maximum plastic strain of the split lock ring

TABLE I.
THE COMPARISON BETWEEN FEA AND TEST RESULTS

Monitors	**Functionality verification**			**Structural capacity evaluation**		
	Maximum hydraulic pressure	*Lock piston stroke*	*Bolt prestress*	*Maximum bolt stress*	*Preload failure point*	*Maximum plastic strain of split lock ring*
Test results	34.5MPa	97.9mm	330.5MPa	398.7MPa	140.8MPa	1.98
FEA results	33.2MPa	98.3mm	321.7Mpa	416.6MPa	137.2MPa	2.05
Relative error*	-3.77%	+0.41%	-2.66%	+4.49%	+2.56%	+3.54

**Relative error = (FEA results-test results) / test results × 100%*

to the maximum bolt stress. The numerical method could satisfactorily obtain the structural behavior of the subsea wellhead connector when external hydrostatic pressure and internal pressure are applied simultaneously. The FEA results are accurate, and agree very well with the test data. It can be concluded that the developed three-dimensional finite element model is suitable for functionality verification and structural capacity evaluation of the subsea equipment.

V. CONCLUSION

A synchronous test platform consists of test setup part and data measurement part was established for functionality verification and structural capacity evaluation of the subsea equipment. Based on this platform and FEA method, a subsea wellhead connector was adopted to investigate its performance and structural behavior underwater. Both FEA and test results could obtain the lock piston stroke, hydraulic pressure, bolt stress and preload failure point with good agreements. For further application, this synchronous test platform could be used for performance study of the subsea equipment under cyclic load and variable load. This paper is also bringing promotional values for other subsea device with similar and even more complex working conditions, such as subsea control module and remote control vehicle.

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This work was supported in part by the National High Technology Research and Development Program of China (863 Project) (No. 2012AA09A204). It is is an extended and modified version of a paper presented at the 2012 International Conference on Artificial Intelligence and Its Application in Industry Production (AIAIP 2012), held in Wuhan, China in December 2012. Manuscript received 19 May 2013. Published as resubmitted by the authors 26 june 2013.