Experimental and Numerical Studies on Concrete Containments Under Accidental Conditions

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ABSTRACT

This paper proposes a synthesis of the main theoretical and experimental results, obtained at that time on concrete containemnts under accidental conditions. Finally, it must be underlined that double walled containments are in all cases able to bring a safer answer to these issues as they make possible, by means of a second concrete barrier to ultimately collect (and then control) the unavoidable leaks of the primary containment; this last remark is, ultimately, strengthened by the fact that, for the latest double walled structures, using high strength concrete, leak rates, through the primary containment hardly overpass those obtained on standard single wall lined containments.

INTRODUCTION

In nuclear power plants, the reactor containment building is the third and final barrier to the outside environment. In FRANCE, two types of containment are used: the 900 MW PWR serie option is a single prestressed concrete wall with an internal steel liner and the 1300 MW PWR serie is double prestressed concrete wall without liner but with depressurised annulus system.

Both structures are designed to withstand the forces associated with internal pressure due to accidental situations in order to provide the necessary tightness to radioactive gaseous products so as to prevent a large release of them in the environment.

For the future NPP generation, it is an obligation to take account of the consequences of severe accidents, characterised by pressure and temperature transients higher than the design curves, in terms of mechanical strengthening and tightness performances.

LEAKAGES THROUGH THE CONTAINMENT

The operation procedures forecast to perform global air tightness tests in order to measure the actual leak rates of the containment during the lifetime of the plant (after the erection, after the first refuelling and every 10 years). The containment is submitted to internal air pressure corresponding to the design basis accident pressure with a safety coefficient.

Basically leakage paths have been classified in three categories [1] :

A - leakages through the containment wall itself considered in its entity,

B - leakages through specific penetrations as electrical ones, personnel air locks or equipment hatch,

C - leakages through the isolation valve of pipes, which go through the containment wall

Double walled containment buildings, widely represented in the French nuclear program led to a more accurate analysis of the leaks through the containment and therefore required to distinguish (see ref [11] , [12]) :

- leaks through the concrete barrier of the internal containment which are not collected in the closed volume delimited by the internal and the external containments and which are consequently supposed to reach directly the environment (usually referred as F_{ed});

- leakages through the internal containment which reach directly the volume delimited by the two containments where they are collected and then treated by means of adequate filters (usually referred as F_e).

LEAKAGE MEASUREMENTS BY AIR TEST

Specific procedures have been defined to allow for precise measurements of the above mentioned categories of leaks and to compare them to the allowable design values. In all cases pressure tests, whether they are global (for the whole building) or local ones are carried out with air; to reach satisfactory estimates of leaks in actual accidental conditions, results must then be adapted to account for the existence in accidental conditions, of an air/steam mixture inside the containment.

Typically containment air pressure tests belong to three categories; each of them intends to quantify the leaks resulting from the distinct types of leakage paths listed in previous paragraph. They are :

- ✓ **type A tests:** Overall integrated leakage-rate test (ILRT) of the containment including penetrations.
- ✓ **type B tests:** Tests intended to detect and measure leaks across penetrations, the design of which incorporates resilient seals, gaskets or other flexible assemblies
- ✓ **type C tests:** Tests intended to measure leaks through isolation valves in process pipes or in penetrations between the inside and outside atmosphere Tests of B and C are usually referred as Local Leakage Rate Tests (LLRT)

The general criteria in air pressure tests retained required for French containments are the following (see ref [11]):

- ✓ for lined containments 0,21 % per day
- ✓ for double walled containments 1,50 % per day

These values are then factored by a 0,75 coefficient to account for ageing of the structure, which therefore leads to the generally accepted criteria :

- ✓ for lined containments 0,162 % per day
- ✓ for double walled containment 1.0 % per day

These values may be compared to typical acceptance levels for the maximum measured leakage rate which are , according to [1] , 0,3 % of the contained gas per 24 h for lined dry PWR containments in LOCA conditions..

To allow comparison, we give in table hereafter the mean global leak rates actually obtained on French containments

Table I-a - Fe as measured on French double walled containments

Type of unit	Fe(%)	Number of tests
P4	0.79	24
P'4	0.90	30
N4	0.35	4
N4 -CV2	0.19	1

Table I-b- Fe as measured on French single lined walled containments

Type of unit	Fe(%)	Number of tests
CP0	0.034	18
CP1	0.021	41
CP2	0.022	38

Table I-c- Fed as measured on French double walled containments

Type of unit	Fed(%)	Number of tests
P4	0.022	4
P'4	0.039	9
N4	0.032	1
N4 -CV2	0.015	1

On theses tables, we can see that the experimental values on single lined walled containemnts are around 10 times less that the air criteria and that the part of the leakage not filtered (Fed) for the double walled containments is in same level of magnitude than Fe for the single wall containment.

Furthermore, it is important to underline that last double walled units of the French N4 program , N4 Civaux 2 (N4 - CV2) where High Performance Concrete was used, exhibited global primary containment leak rates far under the allowable values (0.19%) and even of the same order of magnitude as for lined containments .

DESIGN OF CONTAINMENT FOR LOCA CONDITIONS

Main objectives of the design of prestressed containments, whether they are lined with a steel liner on inside face or simply concrete ones, is to fulfil the requirements of a maximum allowable global leak rate, usually expressed as a percentage of the mass of air-vapour mixture contained in the structure that may leak in a day period. Values of this allowable percentage have been given previously.

Usual procedure for safety assessment of containments for LOCA is typically based :

- on resistance calculations which lead to the definition of a prestress pattern. This calculation, carried out in typical or sensitive parts of the structure, include the need for a residual concrete compressive stress in the containment wall which ranges from 0,0 MPa in case of lined containments to 1,0 Mpa- 2,0 MPa for double walled containments;

- on testing both resistance and tightness performances of the structure by means of full size air pressure conducted at a pressure equal to 1,15 times the design pressure for lined structures and at the design pressure for double wall concrete containments.

Nevertheless, it is quite obvious that air pressure tests, as they are carried out at ambient temperature are not true representations of accidental conditions. Main discrepancies between overall structural integrity leakage tests and LOCA conditions are tied to the thermal effects in the wall which are not at all represented in tests, except for the liner thrust modelled by an increase of the pressure; on the other hand, air pressure tests do not account for the differences in the composition of the gas which generates the inside pressure, air for the tests when it is a mixture of air and steam for the actual LOCA conditions.

Influence of termal loads on concrete

Thermal fields in the wall of the containments induce important thermal stresses significantly modifying the crack patterns in concrete. While this has low influence in case of lined containments, it leads to an obvious increase of cracks lengths and depths in case of Double Walled Containments. Impact of this phenomenon on tightness of the structure may be studied analytically by means of adequate computational methods but it must necessarily be validated using representative scaled models. Numerous numerical approaches have also been performed (see ref [2] , [10] and [16])

- to determine realistic values of cracks depths (however it must be reminded that in LOCA conditions cracks cannot be through cracks) and distributions,

- to analyse more precisely the stress changes at the interfaces between metallic penetration sleeves and concrete that could lead to adherence losses and thus could be at the origin of additional leakage.

Moreover we can notice that in both cases, air pressure tests or LOCA, leaks through the containment wall remains under the control of concrete global porosity (a term to be eventually extended to flows through micro-cracks). Large through the wall cracks, if any, will appear during preoperationnal air pressure test and will be adequately treated and sealed. This kind of cracks would close on th intrados of the wall due to thermal moment induced by the temperature increasing in the wall.

Nature of pressurising gas

When the pressurising medium in LOCA actual conditions is a mixture of air and vapour (even including aerosols), pressure tests are carried out with air, which represents a significant difference as far as mass transfer through the wall is concerned.

Comprehensive studies have been performed on this subject using either analytical approach based on thermo-hydraulic calculations or experimental models. Anyway, however refined the models may be, it must be kept in mind that proper numerical prediction of leakage remain out of reach, due to the impossibility to precisely modelize flows through paths that we cannot correctly define geometrically

Therefore, results of experimental tests (ref [7], [8], [9]) have been used to set the transposition ratio for leak flow through concrete containment wall:

Conservatives values of the ratio between the leak flow with air / leak flow with (air + steam) have been obtained in the range of 1.5 and 3 depending of the concrete type and duration test.

ANALYSIS OF CONTAINMENT BEHAVIOUR UNDER BEYOUND DESIGN CONDITIONS

Containments design, whether these structures are lined or not, is in any case also checked for severe accidental conditions, usually characterised by a uniform increase of internal pressure and temperature induced by an insufficiently controlled accidental situation (loss safety systems), degradation of fuel assemblies in the reactor core, large heat production through chemical reactions).

As an example, the more severe kinematics of such beyond design conditions used for qualification of safety systems are, according to French practice, defined by a continuous temperature rise, at a rate of 3°K/hour, associated with a pressure rise, at a rate of 0,0217 MPa /hour, up to an absolute internal pressure of 0,7 MPa at 24 h after the beginning of the LOCA; this final situation is then followed by cooling of the inside volume of the containment by venting systems.

Similar values have been adopted in current projects developed in foreign countries as for example off design situations defined by a maximum absolute pressure of 0,85 MPa associated with an internal temperature of 200° C in case of lined structures.

Despite the high prestress levels usually met in containments such accidental situations lead obviously to large through wall cracking of the containment concrete shell.

For the EPR project, a maximum absolute pressure of 0,65 MPa and associated to an internal temperature T = 180 °C has been taken into account at the design stage including severe accident sequence.

Analysis of the containment behaviour towards air and gas tightness resorts to two really different approaches whether we consider double walled containments with no liner or lined single wall containments.

For the first family of containments, satisfactory estimates of the global amount of radioactive products that may be released in the environment on the one hand require that the geometry of the cracks in the structure shell should be precisely known (spacing, width for different stress levels, total length per unit surface) and on the other hand that the flow rates of the air steam mixture through the cracks should be evaluated with sufficient accuracy ; as a corollary to this last requirement , physical mechanisms describing the flow in these cracks must be known.

The problem has to be treated in a different way for lined containment for which possible leaks appearing before the structure looses its integrity must be identified. These leaks are closely related to possible liner tears in the vicinity of penetrations, stiffeners or liner anchors, or to the tightness losses in the penetrations themselves (seals, sliding of sleeves in the concrete wall, valves). Analysis of the behaviour of French lined containment has shown that leaks before break of the concrete shell were likely to represent a very limited leakage surface. The problem of releases through these leakage paths has nevertheless to be studied, by in a very specific approach, as it solely concerns interfaces between metallic part of the penetration and concrete, when the latter have lost their adherence to concrete. Leakage estimates then need a detailed search for all possible zones of the where liner tears or steel to concrete adherence losses may occur

EXPERIMENTAL STUDIES ON CONTAINMENT TIGHTNESS

Testing of concrete containments towards tightness follows to distinct paths whether actual structures are submitted to full size pressure tests or scaled mock-ups are tested in laboratory conditions, and usually led to complete failure.

Wherever the actual containments are tested, air pressure tests are carried out at the design pressure (eventually factored to account for thermal effects induced by the liner).

Full size air pressure test

Aims of these tests have double purpose :

- to check the structural integrity of the containment under design load
- to measure the effective flow rates in air, but still at design pressure.

If these tests are able to provide good estimates of leakage rates of the whole containments submitted to internal air pressure (see examples of results obtained in French PWR units) and then by means of assumed correction factors when the latter undergo LOCA conditions (see § III), they do not provide valuable results about crack patterns in concrete in severe accidental conditions. In fact as they are only submitted to design loads, cracking of concrete affects only a few limited restrained zones at base or top of the cylindrical wall or around penetrations, the rest of the structure being protected from cracking by substantial design margins.

Small size concrete samples

Large amount of tests on reduced size concrete samples have been performed , they were aimed at defining laws to correctly predict :

- cracks patterns, width and depth in containment wall,
- leak rates through cracks appearing in concrete, reinforced or prestressed.

In the limited scope of this paper, we will mention hereafter only those of these experiments, which appear directly useful to analyse and study, air tightness of concrete containments.

When [2] gives practical formulas to estimate crack spacing in containment obtained through tests on concrete samples representative of unit surfaces of a prestressed structure, estimates of leak rates through cracks in concrete may be obtained from a set of experimental studies among which we will quote the most directly useful ones in case of a non lined nuclear containment.

[15] provides experimental formulas to describe air flow rates through concrete members subjected to tension stresses, using the concept of equivalent crack which enables to represent given crack patterns. More recent studies [10] allow to obtain more precise estimates of leak rates through concrete members (ties submitted to axial tensile stresses) for airflows under the classical form of

$$q_F = e\,\frac{W_s^3(P_1^2 - P_2^2)}{24\,\mu\, h_r\, rT}$$

in which :

Ws : crack width

hr : thickness of the wall

P1 and **P2** : absolute pressures at both ends of the crack

r : molar constant of the gas

T : gas temperature in the flow

m : dynamic viscosity of the gas

e : coefficient smaller or equal to 1, to account mainly for the geometrical differences between a smooth crack delimited by two planes and actual cracks with much more complex and tortuous geometry's.

[10] proposes for e a relation mainly depending on w and introduce the concept of reduced thickness of the wall hr to represent the influence of secondary cracks which are only surface ones , linked to the re-distribution of tensile stresses to peripheral reinforcement and significantly contribute to the finally measured flow rates.

Anyway the above mentioned selection of tests was aimed at providing proper estimates of leak rates in concrete walls submitted to air induced pressures.

The problem becomes much harder when it deals with a mixture of air and steam which more closely corresponds to accidental conditions met in containment design.

Few experiments have treated this more complex issue .A recent study (see [7]) used cylindrical concrete samples , 0.9 m long and 0.20m or 0.40 m in diameter ,to represent typical part of a double walled containment; samples were submitted at one of their ends to various pressure and temperature conditions applied by an air + steam mixture .Variations of pressure and temperature were controlled under the form of signals equivalent to LOCA or off design conditions; some of the tested samples exhibited pre- formed transversal cracks.

Results provided by these studies were essentially :

- obstruction of concrete pores by steam condensation leads to stop the flow rates within only a few hours from the beginning of the applied pressure and temperature signals at the loaded end of the samples ; condensed steam has the role of an efficient filter to stop gas leaks

- flow rates are always very small ,from 2.5 10-8 m3/s (per unit surface) for the less permeable concrete up to 4.0 10-5 m3/s for permeable and dried samples

- air getting out of the free end of the samples is always very dry which confirm that a very limited amount of steam escapes through the wall.

Results of these last tests were also used to define in analytical approaches an equivalence coefficient between air and air + steam leak rates for accidental conditions and concrete geometrical permeability similar to those encountered in nuclear containments.

Scaled models

Scaled models have been widely used to better approach the development of cracks in containments in off design conditions. Among numerous experiments, which have been carried out in the past years, we may quote :

- French 1/10th model of a typical part of a PWR 1300 P4 unit (see [5]) brought the following results.
  - failure of the model at 1,12 MPa (tendons rupture) is preceded by a uniform distribution of cracks; width of these cracks at failure step indicated that only 1/10 to 1/15 of total strain capacity of rebars is used
  - analysis of cracks width growth during the test allows to determine the pressure (0,82 MPa) at which leak rate through the wall is sufficient to limit any further increase of pressure.

- Experimental studies on a mock-up of the Gentilly-2 containment structure [16] which led to interesting results on crack distribution in prestressed containment walls and yielded useful method to obtain satisfactory estimates of air leakage rates through containment wall [3].

- 1/6th test on reinforced concrete lined containment carried out for the USNRC under nitrogen pressure (see [6]) which provided interesting results among which :
  - a 0,14 % mass/day leakage rate under Integrated Leak Rate Test (ILRT) which appears to be very close to those measured on actual containments.

- test ended at 2,73 times the pressure of the structural integrity test when further increase of pressure became impossible due to extremely large leak through liner tear. The latter appeared in close vicinity of a stiffened part of the liner

❖ The MAEVA project [13] led at present time by EDF and IPSN is aimed at testing a large-scale containment model (ϕ= 14 m, h = 7 m) under air and air/steam mixture in design and beyond design conditions then to failure under water pressure.

The main objectives of this model are :

- to study the mechanical behaviour of a containment beyond its design limits
- to evaluate the leakage rates in air (test) and air + steam (accident) through concrete porosity and concrete cracks
- to investigate the behaviour of local penetration
- to study the behaviour of a composite liner
- to evaluate the retention of aerosols in concrete

The MAEVA mock-up (Fig. 1) has several components:

- a biaxially prestressed concrete cylinder of 8 m inside radius, 5 m height and 1.20 m thickness;
- two prestressed concrete "bases. (mat and cover) of 1 m thickness linked by four prestressed reinforced concrete columns;
- an external metal siding allowing shearing into 6 zones where the leak flows will be measured.

Lastly, in order to obtain a correct simulation of the standard section of a real containment, Neoprene pads, placed at the interface with the bases, leave the cylinder free to radial motion. To ensure correct structural leaktightness, a double elastomeric seal is fitted at the interface between the cylinder and the bases.

The mock-up replicates two standard concreting lifts of the inner wall of a NPP containment. The thickness of the wall has been kept full scale in order to facilitate the interpretation of the leak flow measurement results and their transposition to a real containment (without needing to consider the reduction in scale on the properties of the fluid used to perform the tests). Lastly, about half the inner surface of the cylinder is covered by a composite liner, in order to keep the same volume/surface area ratio as that of a full-size containment and to test several kinds of composite liners.

The mock-up tests represent two types of accident: design-basis accident (LOCA) and severe accident. These scenarios allow for pressure and temperature build-up to 0.65 MPa abs. and 160°C (Fig.2) for the SA conditions (EPR values) and to 1 MPa abs. and 180°C for beyond design conditions during 24 hours. But it should be kept in mind that these scenarios are far more severe than real ones since they are a lot longer.

From a more technological point of view, deformations are measured by vibrating strain gauges combined with temperature sensors. For the air tests, pressurisation is performed by compressors.

For the high-temperature steam tests, a boiler generating 13 T/h of steam with a 30 m3 water tank is used. As for the leaktightness, the flow is deduced from the pressure, temperature and humidity level in each compartment.

The tests have been performed between mid- 98 and mid- 99 and the test results are still under analysis and will be provided at the end of 1999. The first results of the leakage measurement have given interesting information concerning the transposition factor between air and air + steam mixture at the design pressures (SA conditions for EPR project). Despite some local losses of adhesion, the liners tested have keeped their integrity and fulfilled their function in air and vapour conditions.

LEAK RATE COMPUTATION/ THEORETICAL APPROACH

In the same time, predictive calculations of the mock-up by means of a blind benchmark performed in the framework of the CESA project (Containment Evaluation under Severe Accidents), a cost shared action, supported by the European Union. The partners directly involved in the predictive calculations are design offices (Coyne et Bellier, Stangenberg und partners and ISMES), government organisations (CEA/LAMS, LCPC, IPSN and GRS), and a university (ENS de Cachan). These eight organisations were selected for their expertise in prestressed concrete structural analysis. In addition, they use different finite element

Although the eight partners have very diverse modelling and computation methodologies, the greatest differences concern the geometric and kinematics representation of the FE mesh, the material constitutive models and the mechanical characteristics of concrete.

At this stage, the main conclusions of the calculations concerning thermal and mechanical behaviour are quite satisfactory (see Fig. 3), although they are showing some scattering between the different analysis. In the other hand, the prediction of the concrete damage, and consequently the leak flow rate prediction, are very inconsistent and showed that a large effort is still necessary.

CONCLUSIONS

In previous chapters were presented the various approaches used until now to ensure to NPP containment's a necessary air tightness level to fulfil the regulatory requirements essentially aimed at controlling the radioactive releases in case of design accidental conditions. Whereas air pressure tests performed on containments after erection or during their normal operating life allow for regular control of the satisfactory fulfilment of these requirements, it appears that prediction of leakage in case of severe accidental conditions is far more difficult due to the lack of representativity of these air tests for higher pressure levels and high temperature loadings; main causes to this fact lies in the non linear behaviour of concrete and, if the computer codes are now able to predict this mechanical behaviour, the main difficulty encountered remains in modelling the flow processes of fluids through cracked concrete structure. Though a large amount of numerical approaches may be used to address these questions, Probabilistic Safety Assessment of containments brings an original answer to this problem as it allows to quantify, in terms of probability the risks of releases when the containment encounters beyond design internal pressure. Finally, from a general point of view, it must be underlined that double walled containments are in all cases able to bring a safer answer to these issues as they make possible, by means of a second concrete barrier to ultimately collect (and then control) the unavoidable leaks of the primary containment; this last remark is, ultimately, strengthened by the fact that, for the latest double walled structures, using high strength concrete, leak rates, through the primary containment hardly overpass those obtained on standard single wall lined containments.

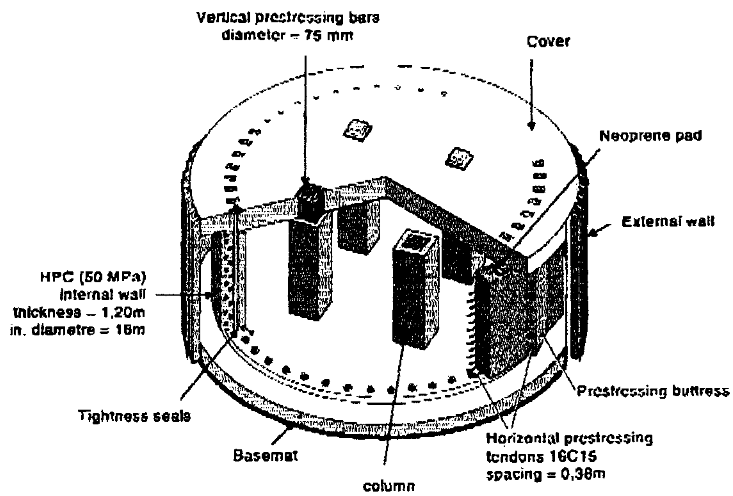

Fig.1. General view of the MAEVA mockup

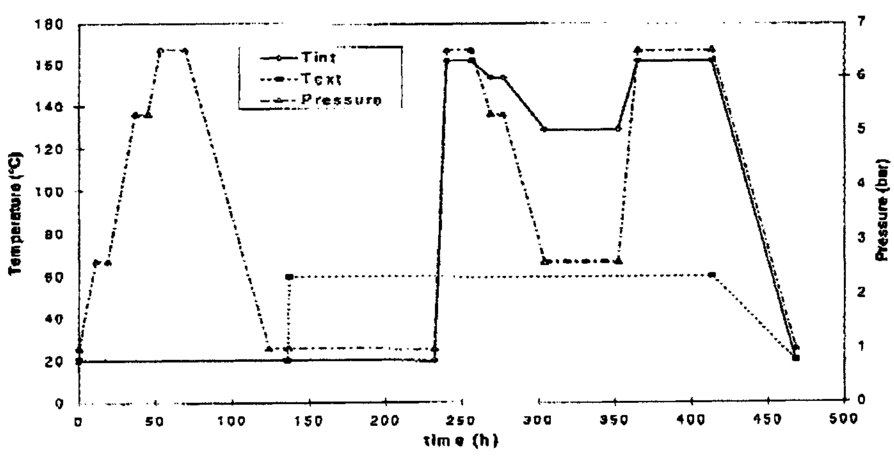

Fig.2. Pressure and temperature tests protocol

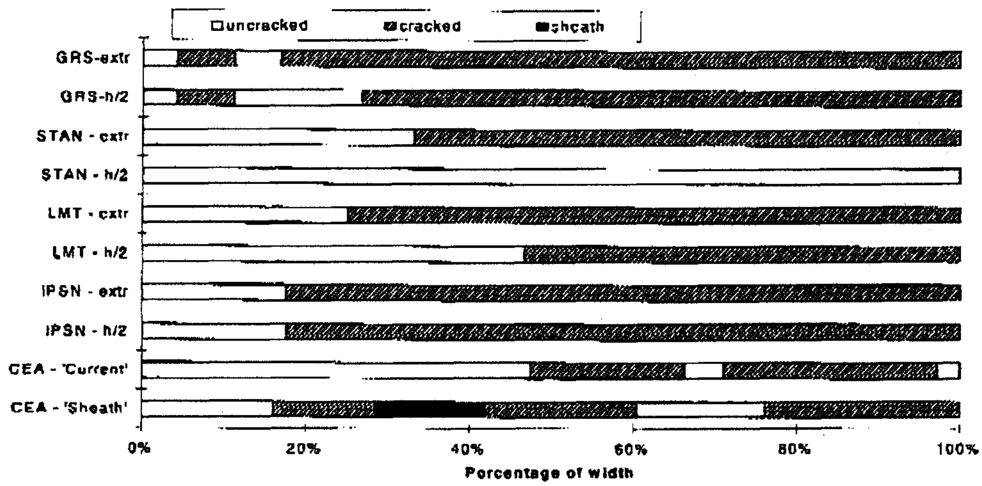

Fig.3. CESA Project- Example of numerical simulation. Vertically cracked width of a current section at 365 hours.

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